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Master Degree Thesis

Investigating real-time feedback of energy consumption and emission data through sonic interaction design

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Abstract

As buildings become increasingly automated and energy efficient, the relative impact of occupants on the overall building carbon footprint is expected to increase. Research shows that by changing occupant behaviour energy savings between 5 and 15 % could be achieved. The definition of occupant behaviour is however highly dependent on the context, and how to successfully develop behaviour change interventions is an open problem. This thesis specifically focuses on the ineffectiveness of Smart Meters based on visual feedback, analysing the reasons behind their faults and exploring alternative feedback methods based on sonic interactions.

This work is an investigation of sonic interaction design methods for energy awareness, based on quantitative data analysis of real-world datasets of historical disaggregated energy consumption. The thesis is divided in two main sections, first energy consumption and emission data in households from Scotland and Sweden have been analysed with quantitative methods, with the aim of extracting knowledge about users´ energy consumption patterns. After the analysis, the problem has been approached from a Sonic Interaction Design point of view, with the aim of developing an alternative, sound-based design to provide feedback about some of the data usually accessed through Smart Meters. A sonic interaction design prototype has been built, using real-world data to simulate household consumption, emissions and energy sources. The final prototype is an energy-aware sonic carpet which provides real-time feedback on home electricity consumption and emissions through sound. An experiment has been designed to evaluate the prototype from a user experience perspective, and to assess how users understand the chosen sonifications.

Résumé

À mesure que les bâtiments deviennent de plus en plus automatisés et économes en énergie, l'impact relatif des occupants sur l'empreinte carbone globale du bâtiment devrait augmenter. Les recherches montrent qu'en modifiant le comportement des occupants, des économies d'énergie de 5 à 15 % pourraient être réalisées. La définition du comportement des occupants dépend cependant fortement du contexte, et la façon de développer avec succès des interventions de changement de comportement est un problème ouvert. Cette thèse se concentre spécifiquement sur l'inefficacité des compteurs intelligents basés sur la rétroaction visuelle, en analysant les raisons de leurs défauts et en explorant des méthodes de rétroaction alternatives basées sur les interactions sonores.

Ce travail est une enquête sur les méthodes de conception d'interaction sonore pour la sensibilisation à l'énergie, basée sur l'analyse de données quantitatives d'ensembles de données provenant du monde réel sur la consommation d'énergie désagrégée historique. La thèse est divisée en deux sections principales; les premières données sur la consommation d'énergie et les émissions des ménages d'Ecosse et de Suède ont été analysées avec des méthodes quantitatives, dans le but d'extraire des connaissances sur les habitudes de consommation d'énergie des utilisateurs. Après l'analyse, le problème a été abordé du point de vue de la conception d'interaction sonique, dans le but de développer une conception alternative basée sur le son pour fournir des informations sur certaines des données généralement accessibles via les compteurs intelligents. Un prototype de conception d'interaction sonore a été construit, utilisant des données du monde réel pour simuler la consommation, les émissions et les sources d'énergie des ménages. Le prototype final est un tapis sonique économe en énergie qui fournit des informations en temps réel sur la consommation d'électricité et les émissions de la maison par le son. Une expérience a été conçue pour évaluer le prototype de la perspective de l'expérience utilisateur et pour évaluer la façon dont les utilisateurs comprennent les sonifications choisies.

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Chapter 1

Introduction

The introduction of Smart Technologies is hailed as an essential contribution to the mitigation of the ecoclimatic crisis. Households are at the center of this investigation, and new Smart Home technologies are a major focus of engineering research, as the residential sector accounts for 25 % of primary energy consumption in western countries [102]. Many proposed approaches involve the introduction of new technologies for monitoring and automating energy-related aspects of buildings. Households are however complex and ever-evolving socio-technical environments, and the design of technology for the home should accommodate such complex dynamics without exacerbating current conflicts and unbalances. Automation does not always mean that users have more control over the infrastructure, it might instead force inexperienced users to interact with complex, often not intuitive systems, in the role of a manager. On the other hand, increasing costs, unstable availability and volatile pricing of energy yield the need for more precise monitoring of energy and immediate, inclusive ways to access complex energy-related data, such as energy forecasts, information about emissions and prices.

A specific focus of this area of research aims at achieving energy savings by acting on the behaviour of users. A common way to do so is providing feedback and incentives to reduce consumption, with technologies such as Smart Energy Meters, which are visual-centered interfaces that provide real-time and historical feedback related to energy. Present and future investment in Smart Metering technology has been estimated at € 51 billion, with the potential for savings ranging from € 14 billion to € 67 billion [29]. Despite these estimations and the huge amount of investments, the real-world studies conducted on the effectiveness of Smart Meters do not present clear conclusions on the amount of savings that have been achieved. In fact, most of the literature about the subject suggests that conventional methods of personal energy monitoring systems achieve modest results on long-term behaviour change for energy efficiency. A possible problem leading to the ineffectiveness of Smart Meters might be their design and their way of providing feedback, which is entirely based on visual communication and might not be engaging enough. For this reason, the study of Human-Computer Interaction (HCI) is deemed important and it is worth exploring unconventional possibilities of interaction for the household environment. This thesis specifically explores sound-based interfaces for real-time energy feedback, in the context of the Sound for Energy project [104] at KTH Royal Institute of Technology in Stockholm.

Not many experiments have been conducted using sound as a medium to provide feedback about energy, and in general the idea of using sounds to convey complex information has been less explored in HCI with respect to the visual domain. Informed by the literature about Sonification and Sonic Interaction Design, this thesis specifically investigates alternative ways to communicate feedback on household-level information that is generally provided by Smart Meters, such as real-time consumption, emissions and the amount of energy being produced by different energy sources. Specifically, this work has been based on the following research questions:

- What information can we gain about people´s energy usage in their homes from quantitative data analysis?
- What are the features that allow a sonic interaction design to display energy information in an engaging and clear manner?

The content of the thesis is organized in this way: Chapter 2 explores the literature relevant to the project in multiple disciplines, such as behavioural intervention studies in engineering and environmental psychology, Human-Computer Interaction, sound perception, sonification and sonic interaction design. An exploration of the quantitative energy data available to the project has been carried out in Chapter 3, investigating the possibility of gaining insight into occupants habits and behaviours which would inform the consequent design process. Chapter 4 describes the design of the sonic interaction prototype that has been built for this thesis, outlining the motivations behind it and the methods used to develop it. The object is an Energy-Aware Sonic Carpet, which produces a sonification of the real-time consumption of the house when stepping on it. The prototype has then been evaluated with a user test, whose design and results are described in Chapter 5. In the end, the overall results of the thesis project and possible future work are discussed in Chapter 6.

Chapter 2

Literature review

The following section is a summary of research that is relevant to the thesis. The overall Sound for Energy project is in its essence multidisciplinary and, to the best of the author's knowledge, very few specifically sound-based interventions for energy efficiency have been explored in previous research projects. For this reason, this literature review analyses the different subjects separately, starting from a review of behaviour studies for energy efficiency related to environmental psychology, environmental behaviour change interventions and the use of smart metering, and then exploring Human-Computer Interaction (HCI) approaches to the problem of energy-related behaviours, Sonic Interaction Design and Sonification theory. Since one of the focuses of the project is non-intrusive sonic interventions, a part of the literature is dedicated to overall research on human relationship to sound from a physical, psychoacoustic and semiotic point of view.

2.1 Occupant behaviour

Designing effective solutions for behaviour change requires a deep analysis of habits of households occupants. This is mainly attempted in this thesis by investigation of quantitative sensor data in relation to household characteristics. The strengths and the limitations of this approach are evident in the following review of literature.

Fortunately, the topic of building occupant behaviour has been approached from multiple different sides and has been object of qualitative and quantitative analysis. Both approaches are essential in this research area; even though every household is different, and behaviour depends on a wide variety of variables in constant change, it is nevertheless necessary, in order to evaluate the effectiveness of interventions, to define quantitative measurements. On the other side - and this is evident from the experiments in this thesis - it is extremely difficult to interpret quantitative results without a qualitative counterpart, that could be in the form of interviews, surveys or workshops.

2.1.1 What is energy efficient behaviour?

The field of intervention design for behaviour change is relatively recent. This kind of interventions have been made much more common by the availability of Internet of Things (IoT) technologies such as sensors and microcontrollers, which allow to collect data cheaply and constantly. The availability of data allows research on the subject to be carried out combining both traditional and computational methods, which have been used to gain more insight into how occupants of houses behave in their environments in the fields of energy engineering, micro-economics and environmental psychology. The first part of this Section describes the main methods employed in research on household occupant behaviour and their results, while the second part is dedicated to environmental behaviour change interventions and their measurement.

There is general consensus in the energy efficiency community on the fact that occupants behaviour is a major driver of energy consumption in household environments [69, 96, 92, 41]. For example, occupant behaviour is commonly identified as one of the main causes of Energy Performance Gap (EPG), the difference between consumption of a building that have been predicted by a simulation and the actual measured ones. Even if, as discussed by Mahdavi et al. (2021) [69], the extent to which behaviour contribute to the EPG is not clear in the literature, it is nevertheless true that occupants have a role in the building's operations, which they can influence passively or actively. As pointed out by the authors, it is useful to distinguish between occupant *characteristics*, which are related to the socio-demographic information and cannot be changed in a short term, and *behaviour*, conscious and observable actions by occupants that could be changed on a short time frame. A first classification of occupant behaviour is offered by Mahdavi et al. (2021) [69], based on the building model feature that is influenced by user actions. Some examples include operation schedules of windows and shading devices, which can influence ventilation and thermal systems, set-point temperature, thermostat settings, system operating schedules and settings that can be different than assumed in simulations and occupant density and schedules, which influence lighting and internal heat load.

These macro-categories of behaviours are really general and do not take into account usage of appliances and specificities of local contexts. Moreover, which behaviours are considered essential and which can be changed by occupants depends on socio-economic status, demography and personal factors and it is crucial to understand which of them can be subject to an intervention and would have long-lasting effects.

The most common way to evaluate behaviour is by measurement of physical parameters of the indoor and outdoor environment. However, as argued by Schweiker (2017) [96] quantitative data is usually not sufficient to completely describe behaviours and do not include behavioural determinants, there is the need to look past physical factors and include social science methods in the calculation.

Overall, behaviour is a broad term, and while exploring the literature on energy-related interventions it is evident that there is no universally recognized definition of behaviour, and each study focuses on different sides of the human activity, depending on the specific interest of researchers. Much research is focused, for example, on human habits' relationship to performances of Heating, Ventilation and Air Conditioning (HVAC) systems [92]. In these instances, the analyzed behaviour is related to how users influence these kinds of systems directly, by controlling physical properties of the building (set-point temperature of the heating system, opening and closing windows etc) or indirectly (appliance usage, presence in rooms etc). Rinaldi et al. (2016) [92] investigated HVAC-related behaviour using a combination of surveys and regression techniques on households metadata (year of construction, building characteristics, apartment size), similar to the analysis in Chapter 3 of this thesis. In their results, HVAC-related behavior was found to be highly correlated to the characteristic of the built environment, especially building year of construction and the socio-economic status of the families considered, with wealthier families tending to be less adaptable and consume more. Most importantly, the authors point out that household inhabitants are prone to adapt to mutating external conditions, and these type of interactions should be taken into account when assessing human impact on building energy performances. Another mixed approach to consider and evaluate behaviours is explored by McKenna et al. (2020) [74]. In this case behaviour is derived by Time Use Survey activity diaries, which the authors converted into network graphs of activity sequences, in order to compare weekdays and weekends. The definition of behaviour is therefore in this case related to how occupants use their time, strictly divided into separate actions.

Households are complex and incredibly diverse environments, and achieving an understanding of how people develop habits in relationship to energy consumption can be extremely difficult. Moreover, these kinds of habits and behaviours tend to shift over time, depending on external (like weather and seasons changes) and internal factors, related to occupants mood and commitments. As many studies point out [48, 5], considering occupants as independent entities leads to rather unfruitful discussions and partial results, because households are essentially social spaces, where continuous implicit and explicit negotiations take place and contribute to develop the set of habits and norms that regulate the everyday life of occupants. This complex entanglement of factors is analyzed by Silverstone et al. [99] in the context of **Moral Economies**, as the unique set of rules, social practices and negotiations that characterize the complex social reality of households. This collaborative reality must be taken into account when elaborating strategies for reduction of energy use. Hargreaves et al. (2020) [48] point out that social relationships should be part of the discourse on energy-related behaviours, as they have significant effect on individuals, from "micro" social relationships in daily life to "macro" social relationships such as class, gender and belief. Relationships contribute to define identity and values, which translate to action and behaviour. Consequently, Hargreaves argues for recognizing the role of social relationships and taking them into account in design and evaluation of products and policies. The amount of factors at play in the definition of these processes is well described from the diagram in Figure 2.1.

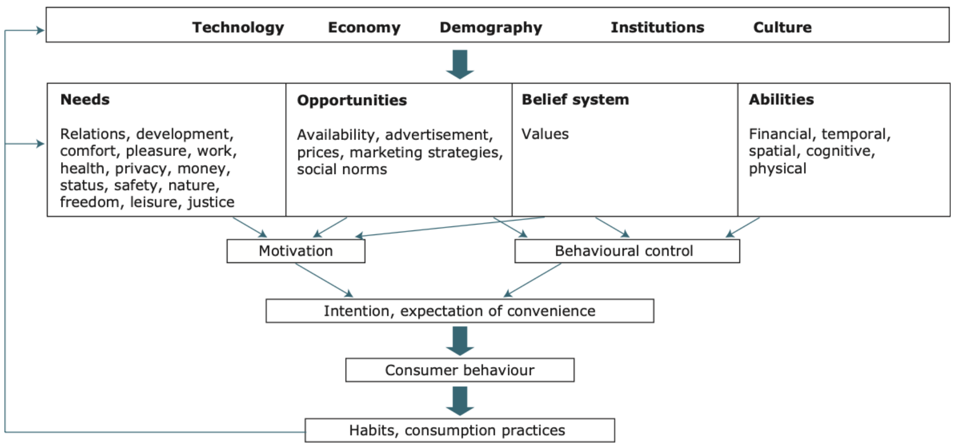

Figure 2.1. Main factors influencing consumer behaviour and practices, from [28]

Social relationships in relation to energy use have been examined by Allcott (2011) [5], in the context of comparative social energy reports. Overall, as pointed out in a European Environment Agency report on behaviour change interventions (2013) [28], behaviour should be considered as dynamic, adaptive processes involving users values, personality and social ties and therefore each study needs to define what it means by household occupant behaviour.

2.1.2 Behavioural intervention studies

Another approach to research occupant behaviour can be the development of intervention studies. Differently from studies considered above, which are mainly based on passive data analysis without major user involvement (besides the collection of data), in intervention studies users have an active role and can be part of experiments for short or longer periods of time. Even though there is no lack of behaviour change studies, much of the literature highlights how the objective of these studies is often not clear, and their methods are not theoretically grounded enough in behaviour change theory and methods [2, 51].

An interesting summary of intervention strategies for energy efficiency is available in the European Environment Agency report on behaviour change interventions (2013) [28]. The report investigates multiple intervention studies on a broad perspective, from broader case studies of policy applications to narrower user-centered experiments. It can be argued that any political intervention has some influence on citizen's behaviour, and in the literature behavior change is in fact described in multiple ways, and interventions can have different levels of granularity. Some examples of policies that are not directly aimed at behaviour change can be regulatory (energy requirements and laws), financial (subsidies and tax incentives), training and education, infrastructure investments and market-based interventions (technology development incentives, certificates) [12]. More direct types of interventions by governments may include information and education campaigns and focused actions on smaller groups of people. Among these actions really popular in the literature are digital behaviour change studies.

Abrahamse et al. (2005) [2] reviewed multiple intervention studies aimed at household energy conservation. In their work interventions are classified under two categories: **Antecedent interventions**, which are aimed at influencing underlying behavioral determinants and **Consequence interventions**, based on the assumption that the presence of positive or negative consequences will influence user habits. The first type of interventions generally involve goal setting, user commitment, workshops and mass media campaigns. Consequence interventions are instead those involving feedback and reward systems at different time granularity. The review highlights that continuous or high frequency feedback tend to be more effective with respect to low frequency. Nevertheless, the authors specify that most studies analysed in their review do not consider long-term effects and do not usually involve statistically relevant amounts of households.

Setting aside the broader, policy-related interventions, a review of behaviour-change studies for energy efficiency [2, 12, 28] yields the following general classification of intervention types:

- **Feedback:** it is based on communicating information about consumption. Feedback can be available to householders in real-time, in the form of digital displays on dedicated devices, computers and smartphone apps, or indirectly, through more frequent bills including historical data;
- **Target setting:** these kinds of interventions are based on dialogue with occupants, who generally select targets of energy consumption for a defined period of time and are invited by the researchers to commit to them. These methods are often accompanied by some sort of feedback measures;
- **Energy audits:** they are household-tailored evaluations by third-part experts which provide users with detailed information about their building, their habits and energy-saving potential. These studies are however often not focused on behavioural features, usually providing advice for longer-term decisions, like investments in a specific technology;
- **Community-based initiatives:** this type of interventions, generally applied to work or neighborhood groups of people, are focused on common target setting and feedback for all people in the group. This has the potential to encourage positive group dynamics, promote individual responsibilities and foster good practice and social norms;

Feedback is probably the most common type of intervention, and the one of higher interest for this thesis. It can be further categorized into **Direct** and **Indirect** feedback [118]. Indirect feedback refers to standard and enhanced billing, while direct feedback involves in-house display and web connected devices for real-time visualization. The data presented usually includes historical comparison of energy audits, energy consumption rewards, energy efficiency advice, social comparison and, in the case of direct feedback, real-time information and appliance disaggregation. The approach adopted in this thesis is mostly related to In-House Display feedback but, as outlined in Chapter 4, the developed interaction methods can be used to account for target setting and in group contexts as well. Positive and negative effects of real-time visual feedback systems are further explored in Section 2.1.3.

Digital feedback-related intervention studies have a typical structure; they usually start with the design of a digital interface tailored for the experiment and the intended users, and then proceed with a more or less long period of testing in which users are asked to use the interface in their everyday life. During the testing phase users consumption and usage of the proposed platforms are digitally monitored, at the end users are usually asked to compile a survey about the user experience, their relationship to the platform and how it affected their attention to energy questions. Depending on the users, interfaces can range from visual displays in dedicated devices [107, 120, 83], smartphone apps [4] to digital games based on real-time sensor data [43]. The data available to the users is in general real-time information about energy consumption with different levels of precision and possibilities for users to navigate the data. Some systems allow to represent the data in different ways, as the same energy consumption quantity can be represented in scientific terms, typically in kWh, but can also be shown as price or CO_2 equivalent (CO_2e) emissions. Different representations can be preferred by different users, depending on individual values and behavioural determinants.

2.1.3 Smart meters and visual feedback

The *Smart* paradigm is an increasingly popular approach to deal with environmental problems in socio-technical systems such as cities, workplaces and households. Ubiquitous computing technologies and IoT solutions for home automation have been hailed as a solution for optimization and reduction of energy consumption in households. Moreover, digital technologies for data collection and processing are being applied to mobility systems and energy grids with increasing success.

Smart buildings allow to collect data in a non-intrusive way [119] and optimize HVAC systems considering user comfort [87]. The data can be used to have accurate predictions of energy demands [11, 55], automate household functions and HVAC systems [91], customize household features for single families and users and gain better understanding physical features by developing building models. These systems get even more complex when households become energy *prosumers* (producer-consumer), as envisioned in common energy narratives and popular technologies like distributed solar and wind power generation. In these cases each building (and their inhabitants) would need to manage not only consumption, but also production and selling of excess electricity to the grid, which introduces increasing complexity and more information to be accessed and managed by users.

The Smart City paradigm is also well accepted on the policy side, with governments contributing to energy-related trends, such as distributed energy production, and experimental policies like carbon allowances, carbon budgets, dynamic tariffs and carbon taxes [12]. These proposals are part of a trend - that of *Smart Technologies* - which generally takes for granted that the users will be happy and have the necessary knowledge to manage complex aspects of their daily life (in this case energy consumption) by collecting and analyzing data about their habits and rationally changing their behaviour accordingly. As later discussed in this Section, this assumption is neither realistic not effective, leading in many cases to conflicts and peculiar power dynamics in the household and yielding the need for a different approach to policy and design. Nevertheless, it is undeniable that in these present and future scenarios the need for methods to account, measure and be aware of consumption in the form of data is increasing, and studying non-intrusive and inclusive interfaces for users to access data is a priority.

This technology-centered approach to environmental problems is increasingly being questioned, on the basis of the sustainability issues related to the growth of such a system and the foundations on which it is based. Setting aside the overall environmental considerations related to the sustainability of the production lines and life cycles of these kinds of technologies - whose questioning is out of the scope of this work - designing devices in a human-centered way requires to examine the faults and problems embedded in the ideas behind this kind of products, and the cultural assumptions on which their design is based, that such products contribute to foster.

A literature review on the subject of Smart Homes by Wilson et al. (2015) [114] points out that there are still challenges to the realization of smart homes, which can range from hardware and software problems to user-centered ones like design and domestication. A growing amount of social science research questions the role of users in smart homes as typically envisioned by their designers, and an increasing amount of domestication-related problems arise when smart technologies are deployed in real environments. Specifically, as emerged from fields studies and workshops [9], the massive implementation of data-related technologies raises question on loss of control, reliability, privacy, trust, cost and irrelevance. Moreover, smart home technologies present barriers related to cost and accessibility, which explains why they are not yet widespread in the general public. Perceived control over building operation can be affected by increasing automation, and it is essential that smart homes are equipped with user-centered interfaces that allow the user to feel control over their living spaces [96]. Occupant knowledge and user acceptance are considered fundamental to achieve significant consumption reductions, most importantly in smart buildings [65, 114]. These issues are further explored in this Section in relation to Smart Meters, a popular energy management and feedback system employed in many studies and commercial applications.

Essential to the paradigm of Smart Homes is the deployment of some sort of Energy Management System to allow users to visualize and interact with energy data related to their house. Investment in such systems is motivated by some proposed long-term advantages, such as the supposed possibility for users to be active and aware of their role in the energy market and, on the energy producer side, having access to user data for demand response, peak shaving and load shifting measures that provide economic savings and better functioning energy grids [6].

The most popular Energy Management System is surely the **Smart Meter**. Even though an increasing amount of literature is dedicated to these devices, there is no precise definitions of what counts as a Smart Meter. Nevertheless, there is a general agreement that a Smart Meter is a device able to measure and store energy consumption data at specific time intervals and enable two-way communication between supplier and consumer for Automated Meter Management [23].

Smart meters are specifically interesting for this thesis work because they provide a very well documented and studied example of interactive objects for energy feedback. Smart meters are fairly standardized in their commercial application, having a usual set of affordances and interactions, and the social dynamics they produce are subject of various studies in the literature. They usually appear as devices with a digital display presenting visual information about electricity use in the form of charts or gauge indicators, as shown in Figure 2.2. These kinds of devices might be coupled with computer or smartphone apps to allow for more interactive data visualization and control. Overall, they are usually only visual interfaces with few potential for interactivity and user engagement.

Potential energy savings due to the deployment of Smart Meters have

Figure 2.2. Examples of Smart Meters

been estimated to 5-15% [22, 28]. These figures are however highly variable depending on modes of feedback delivery and the overall context. Qualitative data shows that users are usually interested in engaging with this kind of technology [16] and become more aware of their consumption, modifying their behaviour at least in the short term. For example, owning a real-time display monitor allows users to identify energy consuming appliances and equate consumption to actual costs. Other interesting positive behaviours that have been fostered by Smart Meters include planning energy use ahead of time, questioning the actual need for usage and overall higher awareness related to other aspect of everyday life, that led users to think more about energy even when it is not measured, such as in offices or when flying [50]. These kinds of actions are, however, specifically user-dependent and require active involvement and will by the user to engage with the information. Moreover, there might be obstacles to the adoption of this kind of behaviours that are not entirely due to the will of the users, but rather to socio-cultural factors and comfort norms.

Despite the great amount of research on the subject, Pierce et al. (2010) [86], identify knowledge gaps regarding some implications of these kinds of systems, such as focusing on specific behaviours and attitudes, considering how feedback is experienced by users, socio-cultural implications, domestication of such systems and philosophical assumptions related to how the "sustainability" and "effectiveness" of these systems are approached theoretically.

Longer term analysis of feedback system show other peculiar consequences. A long-term investigation by Hargreaves et al. (2013) [49] shows that after an initial phase of optimization and adjustment of household routines the visual feedback tends to be ignored by users. Moreover, another possible negative effect is the legitimization of what the users consider to be the norm, even though what is considered ”normal” is related to life quality standards, which are easily shifting toward more comfortable - and therefore likely more energy demanding - habits.

On the social side, smart meters and home automation systems might contribute to reinforce unwanted power dynamics in the household, since not all householders may be capable of controlling these complex systems and they may therefore rely on one specific component of the family (generally a man). Moreover, data collection and display can always raise issues related to surveillance, in this case among family members, with one member of the family observing other member's consumption. [49, 48]

When assessing the impact of energy efficiency intervention it is also necessary to consider the **Rebound effect**. This kind of effect is described as "extent to which the energy saving generated through energy efficiency measures is taken back by consumers in the form of higher consumption" [28]. This effect is well known and studied in many different fields connected to ICT [40]. Rebound effects are divided in three main categories:

- **Direct rebound effects:** increased efficiency makes a product cheaper, which encourages greater consumption;
- **Indirect rebound effects:** savings from increased efficiency on some product enable more consumption on something else;
- **Economy-wide rebound effects:** increased efficiency drives increased economic productivity, which leads to growth and increased emissions on a macro-economic level;

Being the work of this thesis related to behavioural intervention, all of these effects are relevant and should not be underestimated when planning the experiment and evaluating results. For example, the deployment of Carbon/Energy budgets or simply the display of consumption might encourage users to not consume electricity in their houses, using instead their computer to work outside home, essentially not achieving an energy-saving behaviour and building a bad habit which could encourage more consumption and emissions (transit to workplace, consumption in bars etc). An overall review of the literature on smart meters and user behaviour is summarized in Tables 2.1.3 and 2.1.3.

Pros
5-15% consumption reduction
Users familiarize with energy consumption measurements and are aware of their consumption
Higher overall interest in energy-related issues
Users build new habits
Encourages collaboration among household members to reduce energy consumption
Boosts consumer demand and expectation from companies and government to take action

Table 2.1. Pros of visual feedback systems from literature review

Even though these considerations are specific to smart meters and are the result of empirical research, they might be inscribed in a bigger trend in *Smart Technologies*, well identified by Strengers (2014) [105], in which the user - in this case the house occupant - has a very specific, unrealistic role, identified by Strengers as **Resource Man**.

> Resource Man embodies a unified vision for the smart energy consumer. [...] In his ultimate imagined state, Resource Man is interested in his own energy data, understands it, and wants to use it to change the way he uses energy. He responds rationally to price signals and makes informed decisions based on up-to-date and detailed data provided about the costs, resource units (kilowatt hours), and impacts (greenhouse gas emissions) of his consumption. For these tasks he needs information, dynamic prices, and enabling technologies, such as automated smart appliances and micro-generation systems, which allow him to transform his home into a resource control

Cons
Anxiety caused by the constant display of money being spent or CO_2 being emitted
Arguments in the family environment
New forms of gender-biased surveillance among family members
Interest in feedback monitoring falls over time, habits do not tend to stick
Consumption might not depend on user's behavior
There is not much users can do besides changing small habits
Baseline consumption can be reinforced and normalized

Table 2.2. Cons of visual feedback systems from literature review

station. He is both in control of his energy consumption and assigns this control to technologies to manage on his behalf. [105]

In her work, Strangers outlines how these assumptions can be rather unrealistic when confronted with the actual operations of a real household. This is sufficiently confirmed by field studies [86, 48], pointing out the discrepancy between expectations projected on users by energy companies and researchers and the actual effects of smart meters. This might also be part of the reason why energy-saving habits do not stick in the long term: *smart* devices are not designed for the normal operations of a home; they rather envision the home as a power plant. Moreover, there is an evident gender bias in this vision of ideal user, due to the fact that designers of these kinds of technologies are for the most part white middle-class men. Such a bias is even more dangerous considering that women are still the ones that predominantly perform domestic activities, which are overlooked when designing *smart* devices and technologies. An example of such a bias is designing with focus on energy quantities (such as kWh) rather than specific activities (eg. laundry, vacuuming), which are instead how occupants measure their actions in the household.

Despite these considerations, the Resource Man approach is surely the dominant when it comes to *smart* technologies, and continues to attract significant investments. This is most probably due to a combination of lack of awareness about the problems connected to it and by a lack of alternative options to investigate. Strangers proposes some pathways that could be followed for a more effective and inclusive design. Most importantly, she encourages *supporting mess*, re-conceptualizing mess as a dynamic network of routines and patterns that can be explored; another suggestion is *designing for others*, which means taking into account users that are not technically interested in energy bills - such as children, teenagers and animals - but are indeed active part of the home environment. Strangers argues to open the options for design outside of a purely utilitaristic view, broadening the scope of the objectives outside of efficiency and productivity, such as designing for downtime or encouraging low-energy routines in situations of peak demand. This approach requires designers and engineers to consider the cultural roots of and the ideology embedded in the objects and the ideas they are dealing with, essentially making an effort towards *reimagining everyday life*. Some authors that are investigating design approaches that go towards these different kinds of interactions, more human-centered and multimodal, will be further explored in Section 2.2.1.

Overall, it is possible to identify two different trends in the literature. The most popular one - the one to which more resources are currently dedicated - is related to optimization of energy consumption from a utilitarian point of view, it generally views users as independent, rational entities and it focuses on measurable outputs, essentially describing household energy efficiency as an engineering problem [23, 6]. The second trend is much more recent, and it involves considering the problem on a broader scale, identifying the role of social interactions and political action when designing interventions [105, 48]. These two different approaches can be identified as part of two broader views on how to deal with ecological problems, on one side with an optimized, green version of the current *status quo*, on the other building solutions that are actually transformative and challenge the norms, recognizing the central role of cultural processes in consumption behaviours.

2.2 Sonic Interaction design

Despite the fact that sound is a fundamental way in which humans communicate and explore reality, sonic interfaces are often overlooked with respect to their visual counterpart. Sonic interaction design is a branch of Human-Computer Interaction (HCI) disciplines which focuses on sound-based interfaces. Sonic interfaces are inherently different from visual ones and as such, they can be used to convey different types of information, or convey different sides of the same information. The first Subsection of this part of the literature review is an introduction to the HCI methods and theories that have been considered in this thesis, and reports some examples of experimental interfaces for energy awareness. The next Subsection is dedicated to theory of listening and sound perception, fundamental when designing sounds for a specific purpose. After that, in Section 2.2.3, the most common techniques for sonification and Auditory Display of data are introduced and some theory and experiments on the subject are analysed.

2.2.1 Human-Computer Interaction

Human-Computer Interaction (HCI) is the study of how human beings interact with computers. HCI research is strongly multidisciplinary, drawing from disciplines such as design, behavioural studies, perception studies, media studies and computer science. It is investigating these basic elements:

- **User:** an individual or a group of people working together. HCI is interested in users' sensory systems and how they interpret stimuli from digital interfaces. Cultural and personal differences play a role in how people react to interactive objects, having different approaches to learning how interfaces work and how they are domesticated in their environment.

- **Computer:** any digital technology that requires humans to interact with it, ranging from desktop computers to large-scale systems to micro-controllers.

- **Interaction:** humans need interfaces to communicate with computers. The requirements and the granularity of these interfaces are dependent on how much information users need to access in order to successfully operate the system. HCI investigates human usual modes of interaction and applies the knowledge to experimental designs.

Every computer system is designed to accomplish a specific set of actions, which are defined in HCI as **Functionality** [113]. The degree to which the actions performed by machines are clearly exposed to users is defined as **Usability** [59, 111].

HCI research can be focused on entirely digital or physical interfaces, which generally employ sensor-based systems for sensory communication. Particularly important is the concept of **Affordance**, which has been introduced in HCI by Norman (1988) [73]. It refers to the potential of objects to invite users to a particular action.

> Affordances of things are easily made apparent in terms of how young children interact with them. It is difficult to stop a child from kicking or throwing a ball, turning a knob, or jumping on a bed. Luckily, few actions in life are directly afforded - otherwise we would be bored stiff. [73]

Affordances are usually coupled with constraints, which suggest appropriate behaviour. For successful HCI, affordances and constraint should be intuitively suggested by the object. The study of affordances is rooted in psychology, and it can be especially difficult to design affordances for digital objects, since functionalities of these products are often novel and multifaceted. As pointed out by Djajadiningrat et al. (2002) [26], affordances in these kinds of products have been historically linked to the actual interface rather than the function of it. For example, a button might invite the user to push it, but its interface does not inherently communicate the function associated to it. Information obtained by the user can be distinguished between the one obtained before the action is carried out, defined as **Feedforward**, and the response of the product after the action has been carried out, which confirms that the action has succeeded, called **Feedback**. Feedforward should communicate what the result of the action will be and how it is possible to act on the object (the correct affordance).

Specifically, in the application described in this thesis, Feedback has a double meaning: in the developed prototype user action does not only generate a direct feedback related to their interaction with the object, it also communicates a higher-level feedback corresponding to energy usage in the home environment, similar to the one described in Section 2.1.3.

Feedforward is fundamental for the *creation of meaning*, communicating result of an action before it is started. This information is usually communicated by a product's physical appearance, and it can be approached in two ways; the first is using metaphores, iconography and representations, and it is common in only-visual interfaces such as digital displays and screens, the second is direct, and takes behaviour and actions as a starting point. In the second approach the meaning is created by the interaction, usually multimodal - involving all the senses. It is more effective and has more potential when applied to physical objects, because meaning can be carried by more than visual appearance, through factors such as weight, material, texture and sound, which are usually all linked.

Setting aside the marginal role feedforward has in current design of electronic products, feedback is also usually loosely coupled to the digital action. In the real world, action feedback is *inherent*, and to any action corresponds a specific and unique visual, auditory, mechanical and haptic feedback, which communicates different information about the action's status [26]. This concept will be further discussed with respect to sonic objects and sonification techniques in Section 2.2.3.

Another focus of HCI is user perception and the amount of attention interfaces require. Most of the currently employed digital interfaces are command-based, or involve some sort of graphical user input. These modes of communication are defined as **Explicit interactions** [57], where using computers and machines requires explicit inputs and outputs. These kinds of interfaces do not take into account the complexity of non-verbal communication that humans use to acquire implicit knowledge about situations and to interact among each other and with the world. A way to obtain more fluid and user-friendly interfaces is developing **Implicit interactions**, defined as "an action performed by the user that is not primarily aimed to interact with a computerised system but which such a system understands as input" [94]. A way to obtain these kinds of interaction is when the exchange of information occurs outside the attentional foreground of the user. These kinds of interaction require a higher degree of *proactivity* and *presumption* from the computer, which has to be able to sense the *context* [94] and act accordingly without directly asking the user. When assessing implicit interactions, it is important to evaluate the amount of **Attentional demand** they require. Attentional demand is defined as "the degree of cognitive or perceptual focalization, concentration, and consciousness required of the user" [57]. A more attentive evaluation of attentional demand involves looking at aspects such as spatiality, breadth and intensity. A basic example of implicit interaction is an automatic door, which assumes the user is going to enter the door if they are at a certain distance from it, and therefore opens without the need for the user to explicitly act on it. More complex implicit interactions surely require some form of feedforward, to inform the user of the machine implied action through non-explicit communication.

Sound is a particularly suited means for implicit interactions, because it does not require the complete focus of the user's attention. Sounds can be implicitly felt and understood, still providing feedback with minimal attentional demand. Sound-based interactions related to energy will be further explored in Section 2.2.3.

Taking all of these consideration into account, it is arguable that part of the inefficiencies of smart meters - summarized in Section 2.1.3 - could be related to their poor design. Smart meters are exclusively visual-based devices and they provide minimal symbolic feedforward information, which means that they require a really high attentional demand. Moreover, smart meters do not provide inherent feedback when consulted, they are only based on explicit interactions and their reaction to changes in energy consumption is minimal. Experimenting with different HCI methods to communicate the same information becomes an interesting way to tackle this problem.

The topic of energy awareness has been approached from multiple sides in HCI. One of the most common ways to deal with the problem in design research is to explore uncommon interfaces for energy monitoring. These interfaces can range from built and tested objects, to new methods of digital visualization, to speculative experiments and design fiction exercises.

Pierce and Paulos (2012) [84] reviewed some experiments and emerging trends in energy-related HCI. All of the contributions analysed by the authors are based on a novel design artifact, with the main focuses of providing Energy Feedback - generally by digital visualization - and encouraging broader energy awareness and conservation behaviour. Besides papers focused on screen-based visualizations [14, 100, 21, 61, 117], other visual techniques to provide energy feedback include the use of lighting and physical objects, with variable degree of complexity and affordances. Some of the analysed contribution involve subliminal information [45], affordance-based persuasion [103] or gamification [10] approaches. These ideas should be considered for the sake of this project, due to the peculiar properties of sound perception, particularly suited for implicit and habits-based learning.

Some examples of alternative visualization techniques include the Power-Aware Cord [44], in Figure 2.3 and the Energy-Aware Clock [14], in Figure 2.4, lamps that change their color based on energy consumption [85], audiovisual installations [68]. Pierce and Paulos propose a classification of common ways energy has been used in HCI literature. Energy itself or energy metadata - such as energy source, price - can be used as a **material** of design, as explored by the *Static!* research group [7], who are building prototypes to promote critical reflection on energy usage. Design objects can also be related to unconventional ways of **harvesting** energy, such as micro-scavenging devices to capture energy from mechanical, thermal or light sources [81] or hand-powered electrical devices. HCI can also shift the focus from individual users to **communities**, for example exploring interfaces for communication of demand response, load shifting [115] and energy forecasts in distributed settings [100].

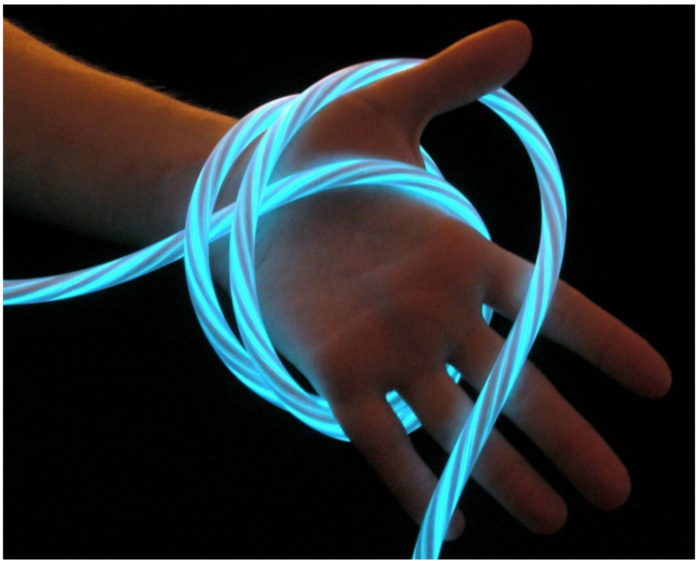

Figure 2.3. Power-Aware Cord [43]

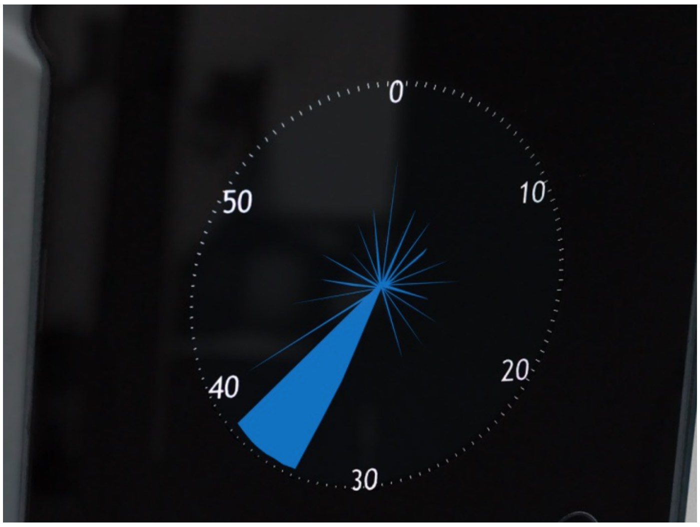

Figure 2.4. Energy-Aware Clock [14]

Design fiction is a common technique used by designers to speculate on future needs and how they could be solved with design interventions. Its use in relation to energy is fairly recent, and it is connected to the increased attention to energy problems, the related trends and the proposed solutions. Nyström et al. (2021) [79] explore different scenarios related to intermittent energy supply, and then reflect on the role of flexible households in the Smart Grid. Distributed generation energy systems are instead investigated by Pschetz et al. (2019) [88], who propose a speculative design object that would trade energy on the market using smart contracts. The authors use design fiction to investigate how different degrees of independence of such a device could affect user perception of control. Gaver et al. (2011) [33] used design fiction and "research through design" to investigate energy independence with inhabitants of the island of Tiree, in Scotland. These kinds of experiments offer multiple examples of energy-related behaviour to experiment from an interaction design point of view. Design fiction exercises can be followed by the development of speculative designs, with the purpose of encouraging public reflections on aspects of technologies and society that are not often discussed, challenging exclusively techno-positive views [25].

Besides energy-focused HCI, another focus of this project is in possibly introducing novel interfaces for the home environment. The sound element, which is the main focus on this thesis, can't be separated by the other senses, so it is useful to explore the HCI literature related to experimental household objects that are not specifically sound-based. As pointed out by Gaver (2002) [34], the home environment has some peculiar properties that should be considered when designing digital devices for it.

> As computing has emerged from the office and laboratory, it seems to have brought along values of the workplace: concerns for clarity, efficiency and productivity; a preoccupation with finding solutions to problems. If, as ethnographers suggest, it takes a lot of work to achieve an ordinary life, then new technologies will help us take care of it. [...] But what if technologies helped us pursue those activities now, directly, rather than merely helping us get the chores done? What if computing helped us pursue our lives, not just our work? [34]

Gaver argues that technology should not be just focused on providing clear, immediate and efficient solutions to practical problems. This is especially true when it comes to devices that should fit in the home, an environment in which users should not be constantly focused on optimization tasks and should feel relaxed, having space for messyness and creativity, as suggested by

Strangers (2013) [106]. Occupant behaviour in homes is not always rational, nor it should be, so there is no reason for digital technologies to be just planned for rational use in these environments. Gaver argues for designers to explore unusual and open-ended goals, building object that encourage tasks such as "goofing around", "exploration" and "sparking new perceptions".

Some examples of objects that fulfil similar purposes are the Drift Table [38] and the Indoor Weather Stations [37]. They are both examples of *ludic design* for the home, which has the purpose to engage users and support "curiosity, exploration and reflection" [38]. The Drift Table is a coffee table with an embedded screen, showing a satellite image map, which moves based on the weight of the objects positioned on the table, in the direction of the object. Users can navigate the map by positioning object of different weights on the table, exploring the satellite image space. The Indoor Weather Station are small devices for environmental awareness, with the purpose of communicating information about the indoor microclimate in an unconventional and engaging way. Despite an initial dissatisfaction with their ludic and environmental information capabilities, the peculiar design of the object made participants show lingering affection for the devices, outlining how designing for the home should take into account aspects other than mere functionality. Another way of introducing interactions in the home environment is, instead of adding a new digital object, to exploit the affordances the are already present in the room itself. This feedback method has been proposed by Menon et al. (2021) [75], whose idea is to shift the focus of design out of a user-centered perspective, adding feedback to the room environment. The authors propose the use of animistic principles to induce empathy for the space in users. In their implementation, the room is equipped with a series of sensors, mini speakers, lights, and vibration actuators for haptic feedback embedded in textile surfaces. This system of distributed feedback is envisioned to communicate general-purpose information about the room state by giving the illusion that the room has *feelings*.

Gaver's suggestions are in line with the reflections by Hargraves (2018) [47] on how to go beyond energy feedback for savings in the home. Besides the consideration on the ineffectiveness of Smart Meters already outlined in Section 2.1.3, a design-related motivation for approaching interfaces in a different way is proposed by Morozov (2013) [78], which critiques quantified feedback for strengthening *numeric imagination*. The limitations of numeric imagination stand from the fact that they encapsulate the problem in the boundaries of the numbers, reducing the task to an optimization problem, locking the users in their pre-existing patterns of consumption. A novel approach would therefore be to develop devices that let users out of numeric imagination, encouraging questioning of habits and practices. Hargraves proposes to accomplish this through **Practice feedback** and speculative design of **Threshold devices** [77, 36]. Practice feedback is based on using disaggregated data to influence small-scale behaviour, for example concentrating on single appliances. Threshold devices are instead devices built with the aim to "open up social settings to the hitherto unapprehended complexity, heterogeneity, and ambiguity of their connections to the "world beyond"" [77]. The aim of such devices with respect to energy would be to connect the household and its inhabitants to the complex network of supply that characterizes energy in their homes. For example by making occupants aware of the limitations related to energy consumption through social devices and metaphors [78], or by displaying energy-related information from the web [35].

Figure 2.5. Natural Fuse device [78]

A particularly relevant example of this kind of device is the Natural Fuse [78]. The Natural Fuse device, in Figure 2.5, is a plant pot with an electrical plug, into which appliances can be connected. The pot is itself connected to a home plug, from which it takes energy. However, the pot allows to flow into the appliance only as much energy as it can be offset by the CO_2 that is absorbed by the plant in the pot. Moreover, all the Natural Fuse devices present in a city are connected to each other on the internet. Users

Figure 2.6. Energy Babble device [35]

Figure 2.7. Solar-Powered website interface [1]

can choose a "selfless" mode of the device, which allows to share their own plant's capacity with other plants. The Natural Fuse is a really good example of threshold device, highlighting how interconnected and interdependent households actually are. Moreover, it concretely emphasizes the limits of energy consumption, which is mostly approached as limitless in the western world. Limits of energy consumption are difficult to materialize in the home

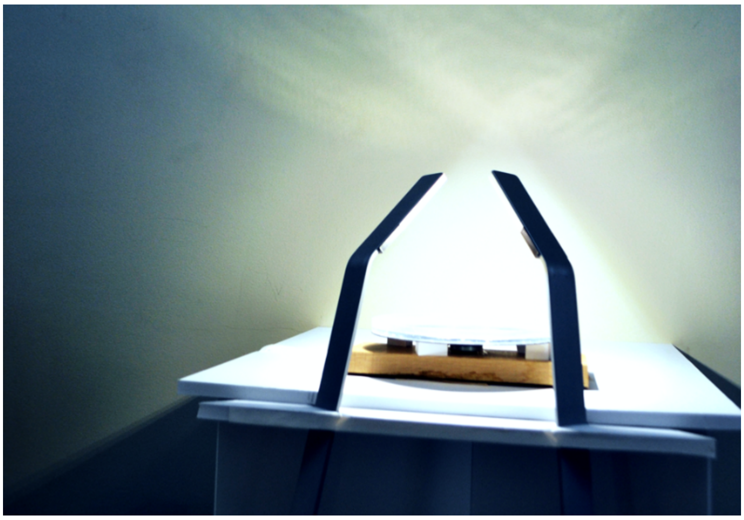

Figure 2.8. Electric-acoustic device [68]

environment, but they are even less evident in digital interfaces such as websites. This idea is at the basis of the Solar-powered Website [1], in Figure 2.7. The website interface shows the energy consumption necessary for the website to work directly on the background color of webpages, which changes depending on how much energy is consumed, and how much is left. This website is entirely powered by a self-sufficient solar panel, which means it can sometimes be offline if there is no solar energy. This constraint raises a series of important engineering and social questions, fundamentally changing the design priorities. For example, in this setting, the website should be designed to consume as few energy as possible, changing the requirement for graphics to include less memory-consuming pictures, animations and fonts. There is also the need to effectively communicate to the users when the website is about to be shut down, and it is interesting to investigate users reactions. Another relevant example of threshold device is the Energy Babble [35]. This peculiar object, shown in Figure 2.6, acts as a randomized radio, picking up news about energy from multiple internet sources, such as Twitter, blogs, news website and official sources. The news is randomly selected and read out loud by a synthesized voice. The Energy Babble is particularly relevant to this project, because it effectively represents a device which introduces new sounds in the house. This device should not be assessed as a utilitarian product, meant to just communicate information. Its confused flow of messages has the purpose of giving a rough idea about the state of the energy discourse, and its users highlighted how it was helpful to think about ways to have better discussions about energy usage.

The peculiar aspect of these devices is that they do not just report information, they also challenge assumptions about what a digital interactive product is supposed to deliver. For example, the solar-power website and the Natural fuse challenge the idea that a resource - a website or electricity - should always be available, emphasizing the limit that these resources actually have and making them tangible. Even if it could be argued that such devices might not be practical in normal user's everyday life, it has to be kept in mind that these are speculative design experiments, which provide valuable insight for future work in terms of domestication, user acceptance and interactions. Even if the prototype developed in this thesis is not properly a threshold device, the insights provided by these experiments were helpful during the development of it, in terms of understanding and evaluating the possibilities for information to be displayed and the degree of direct and indirect feedback that should be shown. Moreover, these examples show how it is possible and important to design devices that challenge the conventional narrative about energy and about home digital devices, allowing for functions that are not purely utilitarian and can engage users in different ways.

2.2.2 Listening and sound perception

Developing sonic interactions requires taking into account that human processing capabilities for sounds are really different with respect to visual stimuli. The perception of sound events is much more transient and strongly influenced by the sounds perceived before. Moreover, attention of auditory events is allocated much differently with respect to visual. Before introducing new sounds in the home environment it is also necessary to understand which sounds are already there, and how do people interact with these sounds. Human perception of sounds can be analysed on multiple levels, from the physical act of listening to the cultural interpretation of sonic events. One of the purposes of this thesis is to identify sounds that people would be happy to live with, and to employ sounds that communicate information implicitly rather than explicitly, requiring a low attentional demand. Tastes related to sound are really personal, and whether people like certain sounds with respect to others does not depend only on personal taste, but also on cultural factors and overall context, since sound perception - especially in physical environments - can't be abstracted from other sensory inputs. A multi-disciplinary analysis allows to understand which - if any - aspects of sound perception can be attributed to *natural* causes (neurophysiology, psychoacoustics) and which to *cultural* causes (musicology, music sociology). Some aspects of sounds can more easily be associated to perceptual features. For example, a sound of increasing loudness can be associated to an approaching object; other aspects, such as timbre, are instead multi-dimensional and much more difficult to associate to a specific perceptual response. These associations are useful tools in the design of sonifications, in which a change in data should intuitively correspond to a change in how the listener perceives the related sound.

Modern technology has allowed sounds to be recorded, altered and reproduced. This possibility has interesting implication on sound perception and semantic characterization, which were investigated by Pierre Schaeffer in his *Traité des objets musicaux* (1966) [93]. Schaeffer defines the field of *Acousmatic* as a phenomenological approach to Acoustics, in which the subject of the study "is no longer a question of knowing how a subjective listening interprets or deforms "reality", of studying reactions to stimuli. It is the listening itself that becomes the origin of the phenomenon to be studied" [93]. The interest in Acousmatic is not only to the "objective" physical properties of sounds - such as frequency, duration, amplitude - but to the act of listening itself, with all of its implication. In particular, Schaeffer defines the concept of *Objets sonores* (Sonorous Object), sounds whose instrumental causes are hidden. When the listener is not able to identify a sound's source, their interest is focused on the characteristic of sound itself. Schaeffer remarks how the practice of listening is not to be considered just as a physical process. Moreover, the change electronic technology impose to sound perception is not only in the possibility to record - thus separating the sound from its source - but also to modify sounds and repeatedly listen to them:

> the repetition of the physical signal, which recording makes possible, assists us here in two ways: by exhausting this curiosity, it gradually brings the sonorous object to the fore as a perception worthy of being observed for itself; on the other hand, as a result of ever more attentive and more refined listenings, it progressively reveals to us the richness of this perception. [...]
>
> We have focused on the physical signal fixed on a disk or magnetic tape; we can act on it, dissect it. We can also make different recordings of a single sonorous event, approaching the sound at the moment of its taping [*prise de son*] from various angles, just as one can film a scene using different shots [*prise de vues*]. Assuming that we limit ourselves to a single recording, we can still read the latter more or less quickly, more or less loudly, or even cut it into pieces,

> thereby presenting the listener with several versions of what was originally a unique event. What does this deployment of diverging sonorous effects from a single material cause represent, from the point of view of the acousmatic experience? What correlation can we expect between the modifications that are imposed on what is recorded on the tape and the variations in what we are hearing? [93]

The relevance of Schaeffer's work for this thesis is in its implications when developing sonic interaction objects and sonifications. The possibilities for user's interactions with such sonic systems are in fact still the same that were identified by Schaeffer, with the difference that, in the case of sonification, variations in sound carry an extrinsic meaning about a quantity which is outside of the realm of sound itself. Nevertheless, the ability of users to correctly interpret sonic outputs is based on their capability of exploring the interfaces and on their familiarity with the sound features that carry the intended meaning.

The reason sound is particularly suited for implicit interactions can be found in how the process of listening attention works. A main difference between sound and visual stimuli is that sound is always perceivable. Auditory stimuli can't be avoided by our brain, so researchers in perception and psychophysics have investigated how the brain is able to focus attention of specific auditory stimuli while ignoring others. **Auditory Scene Analysis** (ASA) is a basic model of auditory perception, introduced by Albert S. Bregman in 1990 [13]. The human ear perceives sound as a variation of pressure in the auditory system, and each ear has access to a single pressure wave at a time. This single wave is the sum of all the pressure waves coming from the individual sound sources. These single sounds are interleaved and overlapped in time and frequency so, according to the ASA model, the brain separates the single sources and recognizes sounds based on heuristic processes that exploit time and frequency regularities to group them together. Such heuristic processes determine our perception of pitch, loudness, timbre and spatial position of the recognized sounds.

Based on this model, it is possible to investigate **Selective Auditory Attention**, the phenomenon that allows to focus on certain sounds in the auditory scene while still perceiving and acknowledging all of them [3]. The psychoacoustics literature suggest that the brain operates a perceptual organization of sounds in order to decide which sounds should be considered as a background and which should be consciously examined [98, 70]. A common example of application of this process is the *Cocktail Party Effect* [15], which uses the situation of a cocktail party to investigate selective auditory attention. The example is related to the fact that in cocktail parties people have the ability to focus their attention on a single specific conversation despite the great amount of auditory stimuli that are present in the room. Nevertheless, our auditory system is at the same time able to monitor the background sounds in order to recognize specific stimuli, such as someone calling the listener's own name, through *Peripheral Attention* [58]. This ability of sound to be unconsciously perceived but still provide information is interesting for the development of interactions that operate at the periphery of attention [17, 8]. It is also important to study the sounds that are often in the background, since they have crucial psychological and cultural significance. Such sounds are often referred to as **Soundscapes**, and are usually analysed in connection to a particular environment [60].

Looking beyond psychoacoustics, human perception of sounds can be approached by semiotics, the study of sign processes and how signs are associated to a meaning. In his article *Towards a Semiotics of the Audible*, Valle (2015) [112] discusses the basics for a semiotics of sounds. The author points out that a semiotic description of sound requires to look at multiple sides of perception, identified in *Actoriality* (sound-affected perception of who, what), *Spatiality* (sound-affected perception of space) and *Temporality* (sound-affected perception of time). These aspects describe different sides of sound interpretation and have to be considered, especially in the case of interactive sounds. Valle points out how a coherent semiotics of sounds requires a theory of listening and a theory of sounds. For both theories Valle uses concepts from Pierre Schaeffer's *Traité des objets musicaux* (1966) [93].

Schaeffer interprets listening as a complex activity identified by different modes of action, described by the French verbs *écouter*, *ouïr*, *entendre*, *comprendre*, each referring to a different cognitive process.

1. *Écouter* (to listen) refers to the process of identification of the causes of a sonic event

2. *Ouïr* (to perceive aurally) shifts the focus of perception to the listener and how the sound is internally perceived by them. It allows deconstruction of the sound based on different perceptual features.

3. *Entendre* (to hear) implies a selection of relevant structural element of sounds, an assignment of qualities - such as rhythm, pitch - with respect to a specific set of values.

4. *Comprendre* (to understand) interprets sounds as a signifier, as a messenger, in relation to what the sound *stands for* in a set of values, with no attention to its perceptual features.

These modes of listening are often intertwined and are operated - consciously or unconsciously - with no particular order, often focusing on different sound events in succession. Valle provides multiple examples of how the analysis of a sound might be composed of two or more of these listening modes in arbitrary succession. For example, in the *Cocktail Party* situation, multiple listening modes are necessary to have a coherent interpretation of the listening process. The action of recognizing a speaker requires *Ouïr* and then *Écouter*, since attention is first focused on the perceived sound and then on the identification of its source. Conversely, it is as well possible to first identify a voice and then focus on the content of the conversation (*Écouter* and then *Ouïr*).

Referring to the application in this thesis, the process of interacting with a sound object or a sonification can as well be described by these listening modes. Specifically, keeping in mind the goal of developing implicit interactions, the listener should ideally engage in *Entendre* and *Ouïr* while learning to interpret the interface while, once they are used to it *Comprendre* should arise automatically after *Écouter*

A theory of listening is complementary to a theory of sound objects. The problem of perceptually-informed sound classification has been approached in a computational way, as done by Merer et al. (2008) [76], which experimented with sound synthesis parameters and perception studies, focusing on the semiotics of sounds evoking motions. Another popular approach is that of perceptually-informed **Timbre spaces**, which aim at representing a subset of sounds by mutual similarity [24]. However, classifying sounds from a semiotic point of view requires considering sounds as both "pure" perceptual sources and culturally defined perceptual objects [112]. Starting from Schaeffer's description of sounds according to seven analytical properties, Valle choses to adopt four of them:

1. *Sustain* identifies the micro-temporal characteristics of a sound. Schaeffer proposes a classification based on mode of sound production, classifying into *sustained*, *impulsive* or *iterative*.

2. *Profile* describe the external temporal form of sound, describing it on the macro domain.

3. *Mass* is intended by Schaeffer as a generalization of the concept of pitch. This notion is based on two dimensions: *site* as a position of pitch in the spectrum, and *caliber*, referring to the portion of spectrum occupied by the sound.

4. *Variation* describes how the mass changes in time.

These criteria allow to define a space of description for sounds which is alternative and complementary to that of timbre spaces, as it takes into account their macro-temporal component. Considering components such as these for sound analysis can be beneficial for sonic interaction design, in which it is much more common to employ physics-related features such as pitch, duration, loudness and timbre as carrier of information. This approach might be due to the fact that these features are mostly familiar to sound designers, however considering higher-level features derived by semiotic analysis could prove beneficial to sonification, as the resulting sounds could be easier to interpret for users who don't have music and sound background.

The case of sonification is peculiar, because an extrinsic *meaning* is associated to physical and perceptual characteristic of sound itself. The level of abstraction of this meaning depends on the specific application. *Meaning* in music and sound is usually less straight forward than in the visual domain. Of course, the complexity of the considered sonic object is an important factor in this regard. For certain sounds meaning can be conveyed by the source, but the relationship between sounds and sources becomes less evident in the case of synthesized and recorded sounds, and even less defined when sounds have a musical connotation. Moreover, meaning can have different definition depending on the scope of the research, ranging from symbolism to emotional content. Research in semantic connotation of music and sounds has mainly explored the correlation between musical and non-musical domains, to study music's *extrinsic meanings*. Some studies focus on simple musical perceptual features, for example exploring the association between the auditory and the visual and spatial domain [27], or focusing on how individual aspects of music influence user's judgement [39]. Music can also be associated to narrative and extramusical imagery [64], gender [110], cultural and religious ideas [56], social contexts and physical spaces [18], with moral and political concepts [97], and emotional content [53, 39]. Particularly relevant to this thesis are the studies related to smaller-scale musical entities such as chords and intervals, and their association to meaning on a neurophysiological [62] and semantic level [19], as sonification usually deals with such small-scale concepts.

2.2.3 Sonification and auditory display

The proliferation of ubiquitous computing technologies and the expansion of internet use are allowing the collection of vast amounts of data. The availability of this huge amount of information is a resource for research and optimization purposes. However, it comes with its limitations: humans often don't have the time or the resources to categorize and explore the data as it is, so computational methods are needed to perform these tasks. The most common way to explore data is trough visualization. Visualization can represent information in formats as simple as charts and graphs or more complex, like interactive installations and display interfaces. **Sonification** or **Auditory display** is the display of data using sounds. As explored in Section 2.2.2, the auditory domain has some peculiar differences with respect to the visual domain, allowing for new and interesting ways to represent data for the purpose of analysis and monitoring.

The reasons for auditory display are multiple and change with the application domain. The auditory system, for example, is able to detect temporal changes and patterns [13] so a proposed use of sonification is to investigate datasets with complex correlations and time changes. Another situation in which this kind of display can be useful is in a work environment where the operator is not able to look at a visual display while performing a task. Moreover, sound perception allows to dynamically focus on multiple sound streams at once and rapid detection of changes. Another reason to explore auditory display is the spread of small IoT devices which might not have a digital display and might need sounds for communication.

As data visualization, sonification can be approached in different ways, depending on the application domain and on the intended public. Sonification is an inherently multidisciplinary research area, involving knowledge from computer science, data mining, psychoacoustics, audio engineering and sound design. As shown in Figure 2.9, the development of a sonification requires to consider the different disciplines in different design stages. Of course, the process outlined in the figure is not usually as linear as it is represented, and a trial-and-error approach is often applied.

The process for the development of a sonification is described in the phases outlined in the Figure. First, it is necessary to acquire domain knowledge on the data to be represented and the public of the sonification. For example, display of data for scientific research would be approached very differently than a domestic data display as in this thesis. Moreover, different data types have different peculiar parameters that can be translated into sound,

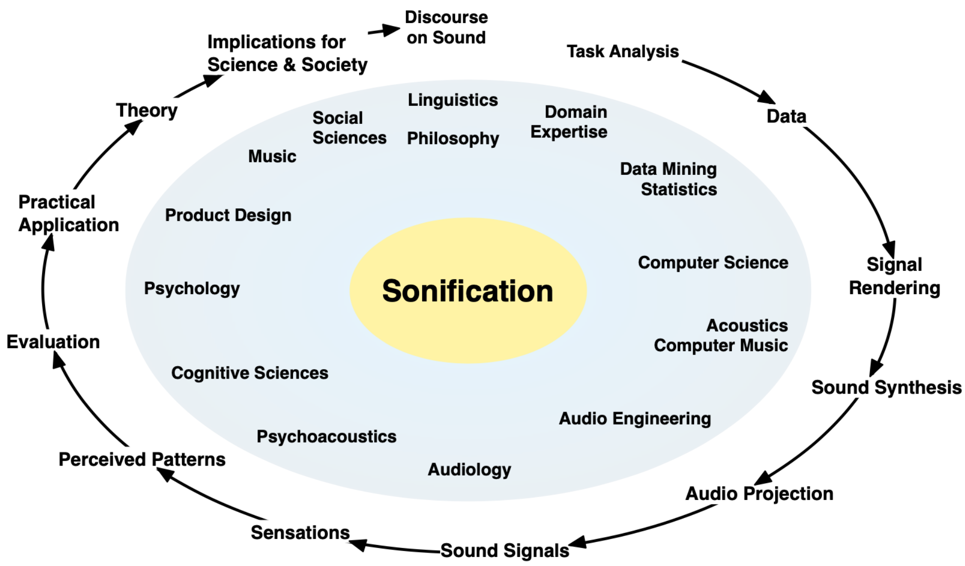

Figure 2.9. Process from development of a sonification and scientific disciplines related to each design phase, from [52]

and understanding the way the data changes is fundamental to understand which sonic parameters can be associated to it. Once the data has been collected and explored, a sonification method has to be established and the designer has to decide how a variation in data influences the sound output. This phase requires a knowledge of audio engineering and digital sound design techniques. The choice of sonification method is different from choosing a sound design technique, because the sonification method determines how the data influences sound parameters, while a sound design technique determines which sounds are produced and which parameters of the sound can be controlled. The main sonification methods are the following [52]:

- **Audification:** it is the most basic way in which data can be translated into sounds. It can be used with periodic time-dependent data, usually involving some degree of frequency or time-shifting of the data to bring it into the audible domain. An example of application is monitoring of seismic activity, in which the audification is used to classify seismic events.
- **Auditory icons:** this approach is probably the most familiar to the general public, because of its common use in desktop computers. Auditory

icons are the sonic equivalent of visual icons in the desktop metaphor, usually short well-defined sounds. They are associated to specific user actions or events, like an application error or deleting a file. The chosen sounds are usually metaphors of sounds that would be associated to such actions in the real world.

- **Earcons:** similar to auditory icons, they are used when there is no direct relationship between the sound and its meaning. Earcons are usually short musical messages, where musical properties and sounds are associated to different properties of the data. Being them more or less arbitrary mappings of musical properties to information, the association between earcons and meanings need to be learned by the users.

- **Parameter mapping sonification:** this is a technique suited for complex and multi-dimensional data. It is based on mapping one or more parameters of the data to sound parameters, such as pitch, duration and timbre. Parameter mapping has the advantage of being a highly flexible method, that allows to obtain complex sonic outputs and represent complex information, however there is no established method for choosing which sounds are mapped to which parameters of the data. Design choices play an important role when using this technique, and the mapping can differ substantially depending on the application and the kind of user.

- **Model-based sonification:** this method is based on emulating sonic feedback in physical systems to provide information about data. It requires the creation of sound-producing processes where data is an integral part of the system. These *sonification models* are usually inspired by physical systems; normally silent, they require an excitation and change dynamically depending on the user's interaction with the system.

Sonification is a recent discipline and therefore, besides the aforementioned techniques, no standard method has yet been established in the literature for specific tasks and application domains. The experimental stage of this research field means that the design of a sonification is mostly based on heuristic techniques that involve a certain amount of arbitrary design choices. This openness means that the design process for sonification is usually based on trial and error, and involves to a certain extent the personal tastes of the designer.

A focus of this thesis is the development of a sonification that is accessible and non-intrusive for the average user, and that would be suitable for the home environment. This requires not only to choose intuitive sound mappings, but also to think of a coherent way to access those sounds. Sound-based digital interfaces are studied in **Sonic interaction design**, a branch of HCI whose focus is not only representation of data (as in sonification), involving all kinds of sound-based interactions between humans and computers.

Human interaction with any object involves a sonic component. The process of this "analog" sonic interaction begins with a mechanical action carried out on an object, and the mechanical displacement of some component of the object results in the production of a sound, which informs the listener about object properties [32]. This process has to be taken into account when designing digital sonic interactions. Since digitally generated sounds are usually added to the regular sounds produced by the object chosen as an interface, their response to user actions should be similar and inspired to the object's natural sonic response, the one users expect and are mostly familiar with. Moreover, every physical interaction is multi-modal by definition. Since all the senses have a perceptual effect on the user, it is a good practice to explore and evaluate other perceptual components such as visual and tactile when designing sonic objects. Sonic interactions with physical objects become even more complex when the user is interacting with a sonification. In this case - which is the situation explored in this thesis - the sonic output is produced by both the user interacting with the object and the data being represented. The process of user interaction with such an object is described in Figure 2.10.

Another specific application field that is useful for this thesis is **Ambient auditory display**, which is concerned with representation of data in space. As in the case of this project, ambient sonifications are meant provide information about some characteristic of the environment where they are located, and sounds should integrate with the already present soundscape. Ambient sonifications have been used multiple times in environmental applications, such as water toxicity [30], real-time pollution data in urban environment from complex sensor networks [101].

Energy has been a quite popular subject for sonification, with multiple experiments focusing on energy awareness and household applications. Fickert et al. (2006) [31] presented *SonEnvir*, a sonification software, and its application to complex oscillating behavior of electrical power systems. The authors experimented with sonification methods to find disturbances in the power grid. Their research shows the potential of sonification to highlight physical qualities of electricity flows in a more evident manner with respect

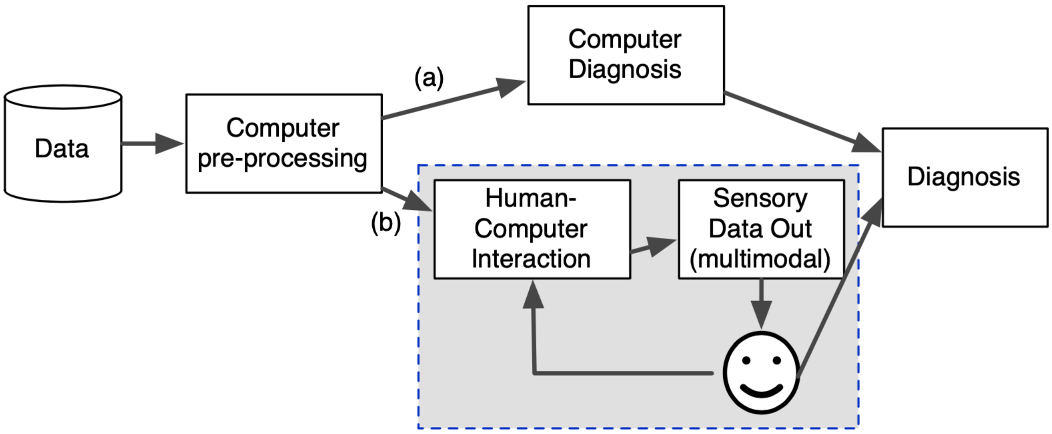

Figure 2.10. Model of user role in interactive sonification, from [52]

to visualization techniques. In particular, sound allows for a better time sensitivity and for increased characterization of complex phenomena through synthesized soundscapes. For example, specific phenomena might be highlighted by changes in the harmonic spectrum, ringing sounds, distortion and phase shifts. Power grid data has been approached also by Cowden and Dosiek (2018) [20], who sonified frequencies and voltage variations in a grid, suggesting also a design for a real-time grid sonification device.

Household consumption has been approached by Hammerschmidt et al. (2013) [46], who propose a system to sonify water consumption in the shower. In their experiment they use blended sonification, combining ambient sounds with synthesized ones, to give personalized feedback about the cumulative energy consumption in the shower time. Groß-Vogt et al. (2018) [42] propose a sonification of the electric power consumption of an institute's kitchen. Based on the Parthy's investigation of reverberation as a carrier of ambient information (2004) [82], in this project the reverberation of a room is changed depending on the difference between the current consumption and a weekly baseline. This approach is defined as *auditory augmentation* because it changes the perception of ambient sound but not the actual sonic content of the room. Moreover, being the augmentation constantly present, it should not disturb communication in the kitchen environment. The authors remark that the designed system is self-adaptive and not judgemental of the absolute level of power consumption, as the output is relative to the previous weekly consumption. Another approach to household energy data is *Powerchord*, a project by Lockton et al. (2016) [66]. It is a system for energy feedback with real-time sonification for user behavioral change. The authors have conducted multiple workshops with residents which led to different sonfication ideas. Working on the project, the authors developed *Bird-Wattching*, the sonification of power consumption in the kitchen using bird sounds, outlined in [67].

Chapter 3

Data Exploration

The main data sources of the project are three datasets:

- The **KTH Live-in Lab dataset** [63] collects energy consumption and environmental sensor data related to student accommodation buildings at KTH Royal Institue of technology. KTH Live-in Lab provides data from a single building with multiple very similar apartments. Measurements about the whole building and external conditions are provided along with data from single apartments.

- The **Svenska Kraftnät** [109] is the Swedish authority that is in charge of maintaining and developing the Swedish Energy Grid. They collect information about the energy production and consumption of the national Swedish Grid and make them available on their website.

- The **IDEAL household energy dataset** [90] collects energy and environmental sensor data from 255 UK homes over a 23-month period.

Although fairly recent, the IDEAL dataset has been used in multiple contexts, such as inference of domestic heating usage [11], statistical comparison on heating usage [89] or to propose new visualization method for user engagement [116].

The data exploration in this thesis was approached in an open-ended way, with the objective of identifying interesting behaviour-related connection using typical data science quantitative methods. The main outcomes are described in the current Chapter. As stated in Section 2.1, this analysis suffered from the lack of behaviour-related qualitative data related to the users, which did not allow to identify specific habits. However, these large-scale quantitative results confirm the correlations between consumption and household characteristics that have been referenced in the literature. Moreover, the data exploration phase has been extremely useful in relation to the design phase described in the following Chapters; data can be viewed in this case also as a design material, which significantly contributes to the aesthetic result of the sonification, and analysing its structure, correlations and periodicity allows to identify interesting direction in the sonification phase and exclude unfeasible approaches.

3.1 KTH Live-in Lab dataset

KTH Live-in Lab [63] is a smart building and student accommodation in Stockholm (Sweden). It is a good example of application of many experimental home energy technologies described in Section 2.1.3. The building is equipped with an experimental sensor network in constant evolution, measuring data about environmental variables such as rooms temperature and humidity, electricity consumption and distributed production, user presence, CO_2 concentration in rooms, ventilation and heating systems. The data that have been used in this project are part of a specific dataset, which has been collected for a different, not yet published, research project. This dataset collects per-appliance energy usage in the main Live-in Lab testbed, an apartment in which four students are living. The consumption of each of the appliances in the house has been monitored and recorded over 280 days (27th August 2020 – 2nd June 2021).

The work of this thesis does not involve single appliance consumption, so the per-appliance data has been aggregate to investigate historical total electricity consumption of the overall apartment, in order to examine household-level consumption patterns. Moreover, historical analysis is useful to speculate on the settings and the thresholds for the prototype described in Section 4. Aggregate data allow to investigate habits related to periodicity, as shown in Figure 3.1, which portrays average electricity consumption by weekday in the apartment.

The effect of householders on the environment is not only due to user behaviour and not even just to their consumption. An analysis of where the energy a building is consuming is coming from allows to have a deeper understanding of the impact of such a building on the environment regardless of occupants behaviour, in terms of carbon footprint. The aim of such an analysis is to acquire general knowledge about the composition of the Swedish energy grid and how each person's consumption could be affected by knowing

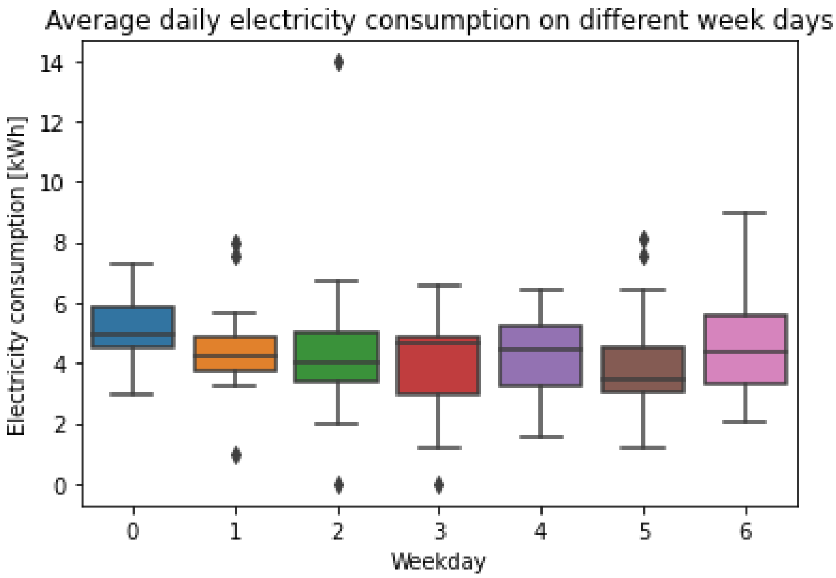

Figure 3.1. Average daily consumption on different weekdays in the KTH dataset

the sources of production of the energy they are consuming.

A dataset from Svenska Kraftnät [109] has been used to calculate the carbon footprint of the KTH Live-in lab apartment, in CO_2 equivalent (CO_2e) unit measure. This dataset collects historical information on energy sources contributing the Swedish Energy grid. The data is composed of hourly information of power production from wind, hydro, nuclear, geothermal, solar and other energy sources. The information has been collected from the 1st January 2021 to the 31st October 2021, and it accounts for energy consumed in the Stockholm area, where the KTH apartment is located.

The energy production data has been used to build an historical dataset of overall consumption and emissions in the KTH Live-in Lab testbed apartment over the period between the 1st January 2021 and the 3rd June 2021, which is the intersection between the data collection timings of the KTH Live-in lab and the Svenska Kraftnät dataset. Figure 3.2 shows the percentage of production by each of the considered sources in the chosen period of time.

The data from Svenska Kraftnät, which measures absolute quantities of energy production at any point in time in MW, has been converted to percentages of production from each source in each time interval. These percentages have then been multiplied by the KTH consumption data in the same time interval to obtain virtual quantities representing how much of the energy the house is consuming comes from each of the sources. To calculate

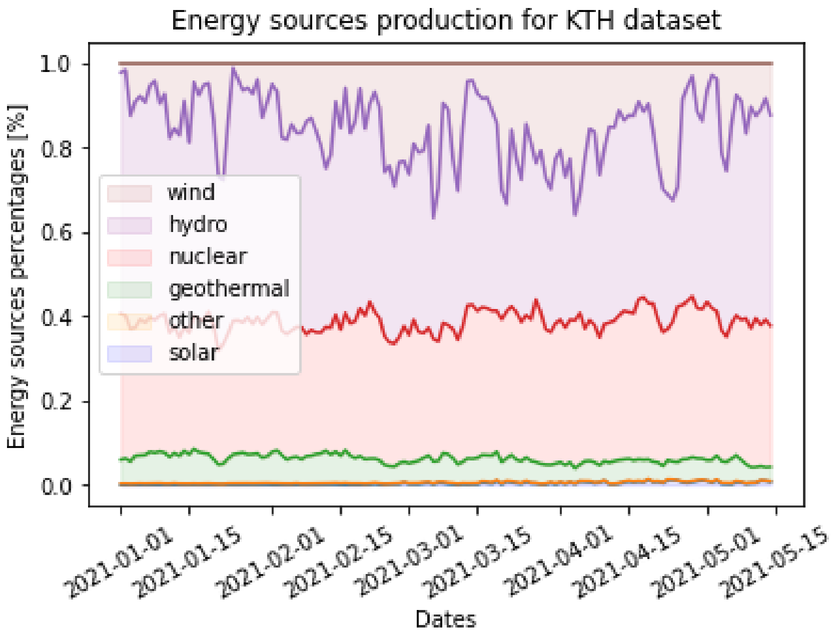

Figure 3.2. Energy production from different sources in KTH Live-in Lab dataset

total household emissions in any time interval each of these virtual quantities have been multiplied by an *emission factor* for each source, which roughly represent the amount of CO_2e emitted for each kWh of energy that has been produced from an energy source. The emission factors for each of the energy sources involves a complete life cycle assessment of energy production systems [71], evaluating production materials and production emissions. The emission factors that have been used in this thesis are collected in Table 3.1. They have been taken from the IPCC 2014 report [54]. For simplicity, the emission factor for the "Other" category is the average of the categories "Coal", "Gas" and "Biomass", which are not measured in the Svenska Kraftnät dataset.

These factors allow to roughly estimate the CO_2e that has been emitted by the home at any specific point in time in the dataset. Figure 3.3 shows the historical electricity consumption, while Figure 3.4 shows the correspondent calculated emissions.

It is easy to see that consumption and emissions are in this case strictly coupled. This is easily explainable by looking at Figure 3.2 and Table 3.1: even if production by each source is oscillating, most of the energy is produced by low-emitting sources like wind, hydro and nuclear. Of course, a

Energy source	**Median emission factor [CO2e g/kWh]**
Wind	11
Hydro	24
Nuclear	12
Geothermal	38
Other	519
Solar	48

Table 3.1. Emission factors used for calculation of carbon footprint, from [54]

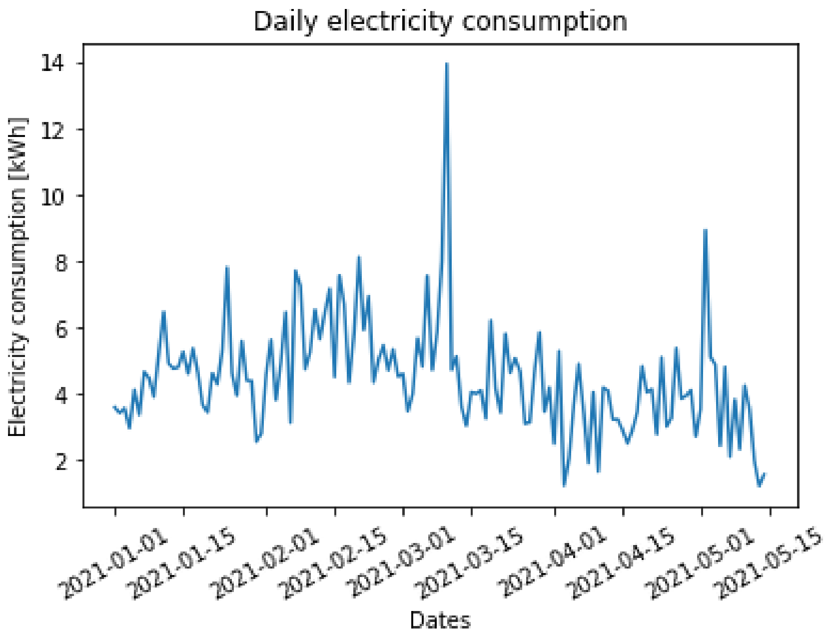

Figure 3.3. Daily energy consumption in KTH Live-in Lab dataset

more thorough analysis would involve specifically calculating emission factors related to the type of plants used in the Stockholm area. Nevertheless, the purpose of this analysis is to inform design-based intervention, and it is therefore acceptable that it has such a margin for error. Moreover, the dataset that has been produced for analysis has also been used for threshold and mode setting and to simulate realistic consumption in the design phase, described in Section 4.

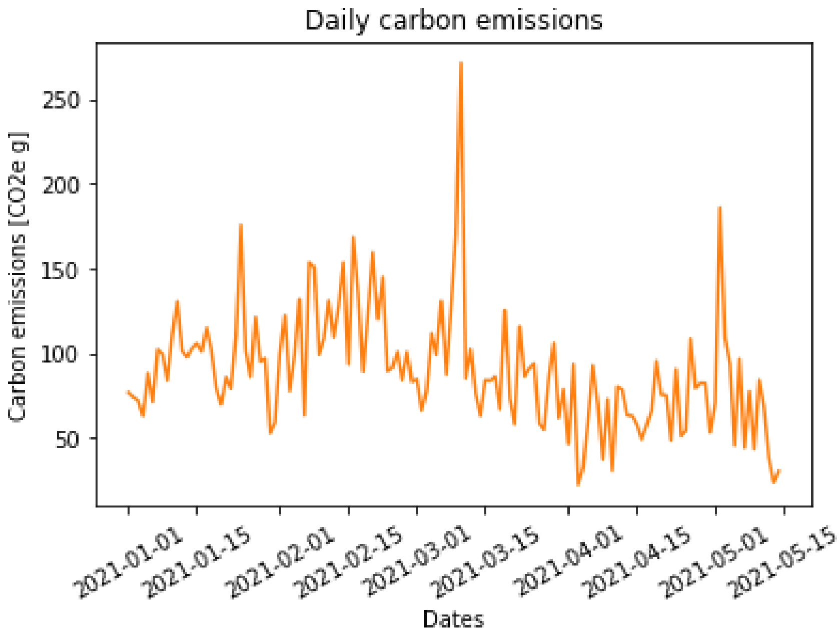

Figure 3.4. Daily carbon emissions in KTH Live-in Lab dataset

3.2 IDEAL dataset

The IDEAL energy dataset has been used in this thesis mainly to investigate the relationship between occupant characteristics and energy consumption. The authors of the dataset have developed a sensor network for Non-Intrusive Load Monitoring and installed it in homes of voluntary participants in Scotland (UK). The dataset contains measurement of temperature, humidity in rooms, electricity consumption, gas consumption, water temperatures and water flows. 39 houses out of the total amount were provided with an "enhanced" sensor system which include measurements of individual electrical appliances and subcircuits. The data has been collected over a span of 23 months, from July 2016 to June 2018, but measurement periods are different for each household.

This data is provided in the format of time series, with seconds-level precision. An example of electricity consumption data for a whole day is shown in Figure 3.5. The plot shows all the available electricity measurements in home 145 on the 14th of January 2014. It is easy to see that, despite it being an "enhanced" household, the monitoring of individual appliances is not comprehensive and there is still some amount of consumption that goes untracked and can't be associated to any specific appliance and therefore to any specific consumption pattern.

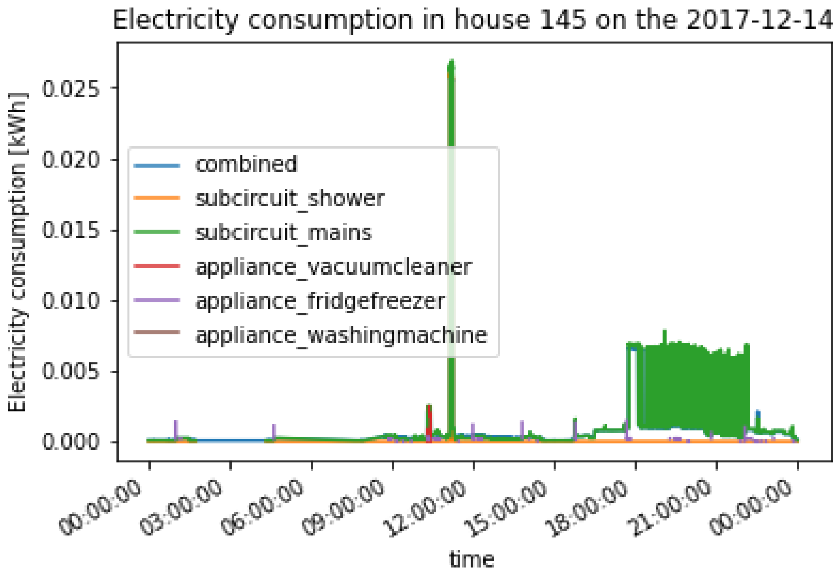

Figure 3.5. Time series energy data for house 145 on the 2017-12-14

From the time series data on overall household consumption it's possible to gain information about behaviour by exploring the seasonality of the data. An example is shown in Figures 3.6, 3.7 and 3.8, which portrays average consumption in each day of the week over one year of measurements of three example households.

As can be seen from the box plots, different household have different habits of weekly electricity use. This is especially visible in house 268, in which consumption rises significantly during the weekends. More information could be obtained by looking at the variance of house 146, which is much larger than other houses, showing that people in this house have had shifting habits during the measurement period. Moreover, the absolute level of consumption is really different among the houses, with home 146 consuming on average much more than the other two homes. The reasons for that can be intuitively understood by looking at the metadata corresponding to each of the houses. For example, home 146 was built in the period 1931-1944, it has 4 residents, and it is an independent house (not a flat). In contrast, home 255 is a flat inhabited by three people, built in the 1850-1899 time period and home 268 is a newer independent house inhabited by one person. These differences might explain the differences in absolute levels of consumption, and the lower

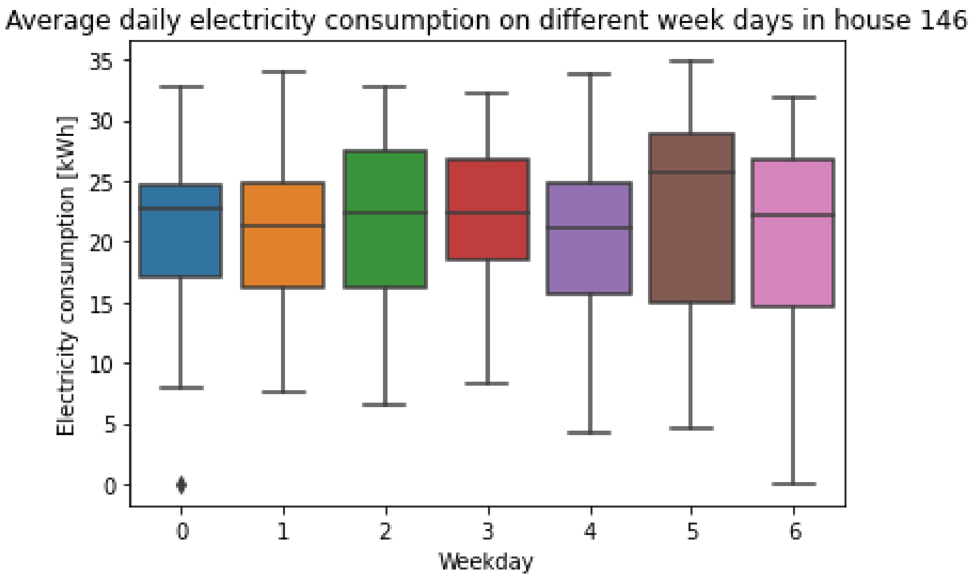

Figure 3.6. Average daily electricity consumption on different week days in house 146

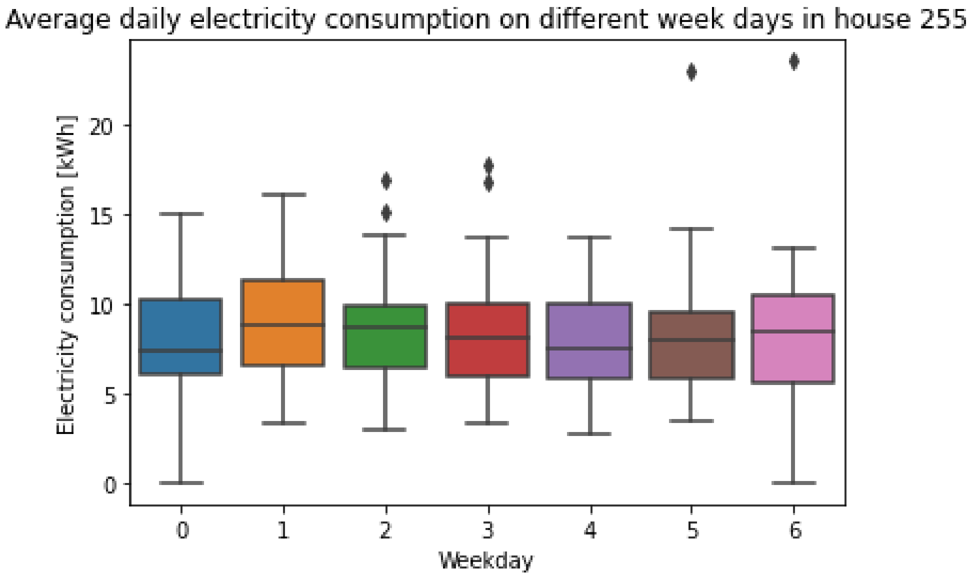

Figure 3.7. Average daily electricity consumption on different week days in house 255

variance in the weekday averages of home 268: it's reasonable to assume that, since it only has one inhabitant, their habits will be more regular.

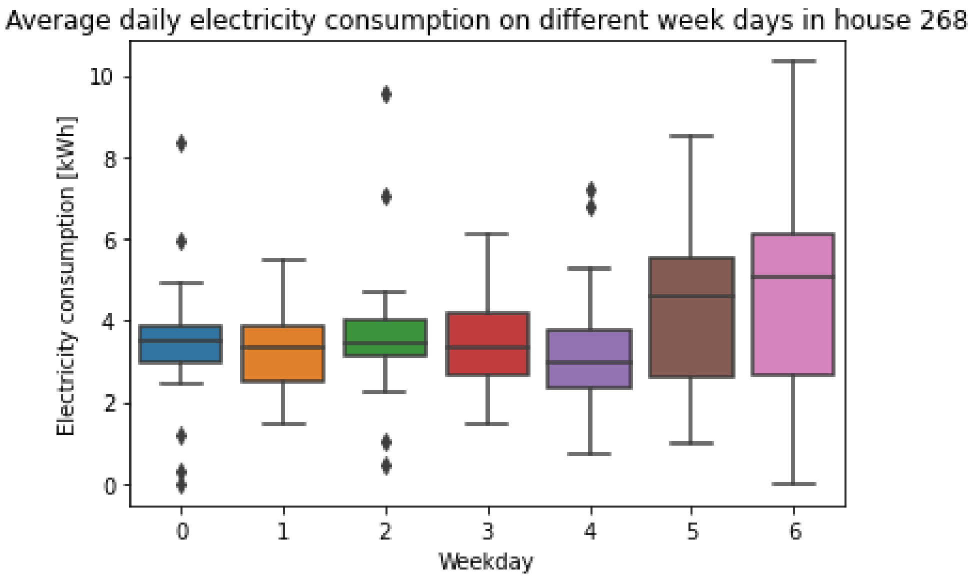

Figure 3.8. Average daily electricity consumption on different week days in house 268

The correlation between household characteristic and average consumption can be investigated over the whole dataset with computational methods, thanks to the extensive metadata about each household provided by the IDEAL dataset. This metadata includes information such as the number of occupants, number of rooms and income category of each household. To connect the metadata to the actual consumption values it is necessary to perform some pre-processing on the time series information. Since this analysis is focused specifically on electricity consumption and user behaviour, for each household some overall indicators have been extracted from the related time series data, like average daily energy consumption $[kWh]$ and average per-capita daily energy consumption $[kWh]$. The following analysis has been carried out using per-capita consumption because of the specific interest of this thesis to single user behaviour.

The bar chart in Figure 3.9, gives an idea of the internal diversity of this dataset, with some household consuming more than 14 kWh daily and some others less than 4 kWh. Specifically, per-capita consumption allows to see that these sharp differences are not only due to having more people in each household, but also to other unknown factors. Even though some of the differences in consumption might be unavoidable due to essential reasons, some others might be superfluous, and it should be indeed possible, if it's possible to identify them, to significantly reduce them.

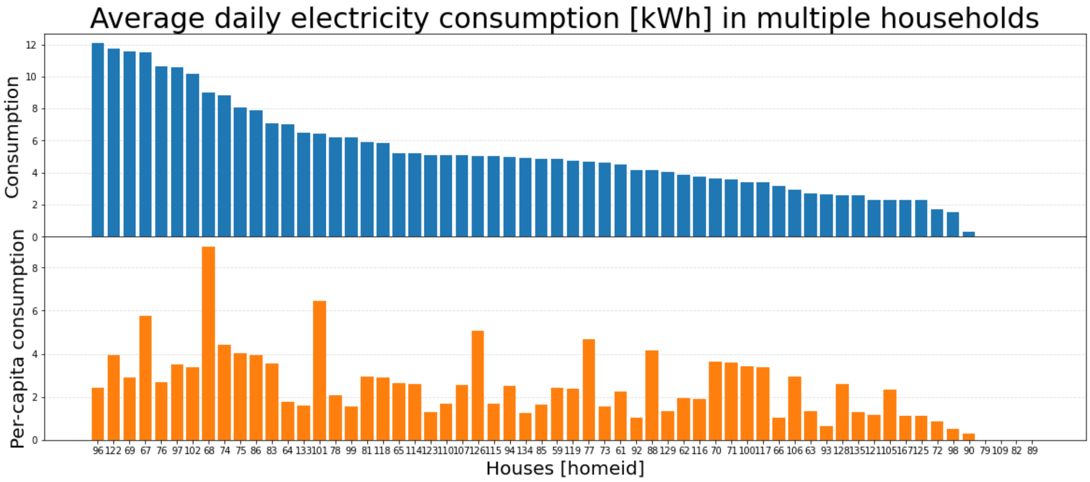

Figure 3.9. Average daily electricity consumption computed on selected houses with at least one year of data

Some basic computational methods have been used to investigate the correlation between household characteristics and per-capita consumption. Among all of the household metadata provided by IDEAL, Table 3.2 shows the ones that have been considered in this analysis.

Before investigating correlations in a numerical way, it was necessary to handle the many categorical features in the metadata. Some categoricals, like income bands and build era, could be interpreted as increasing integers and were therefore converted in that way. Other features, like location (in this case Edinburgh or Midlothian) and house type (flat or house/bungalow) have been mapped as single binary features. After conversion of categoricals, the easiest way to investigate correlations is to look at the correlation matrix of the dataset. The correlation matrix collects the pairwise correlation coefficient among each features. The correlation coefficient between two random variables X and Y is defined as:

$$\rho_{X,Y} = corr(X,Y) = \frac{cov(X,Y)}{\sigma_X \sigma_Y} = \frac{E[(X-\mu_X)(Y-\mu_Y)]}{\sigma_X \sigma_Y}$$

Figure 3.10 shows the correlation matrix of the resulting features.

From the matrix it is already possible to observe some interesting correlations, most of whom were expected and confirmed the theoretical literature on the subject. Some examples might be the positive correlation between average electricity consumption, number of residents, number of rooms and

Feature name	**Data type**	**Description**
Per-capita electricity consumption	Numerical	Electricity consumption for each person in the house
Location	Categorical	Location of the house (between Ediburgh, Midlothian and West Lothian)
Number of residents	Numerical	How many people live in the house
Income band	Numerical	Category of income of the household by income brackets in increasing order (eg. "£48,600 to £53,999" or "£90,000 or more")
Hometype	Categorical	Type of building construction, either "Flat" or "House or Bungalow"
Number of rooms	Numerical	Number of rooms of the building
Urban-rural name	Categorical	Category of urban area the house belongs to, either "Large Urban Areas" or "Small Town or Rural Areas"
Build era	Numerical	Year brackets when the house was built, in increasing order (eg. "1900-1918" or "Before 1850")
Occupied days	Numerical	How many days in a week is the house occupied (on average)
Occupied nights	Numerical	How many nights in a week is the house occupied (on average)

Table 3.2. Features used for statistical analysis of consumption on IDEAL dataset

occupied days and nights. Per-capita electricity consumption is also positively correlated with house/bungalow structure types and negatively correlated with flats, confirming the intuition that large houses consume more.

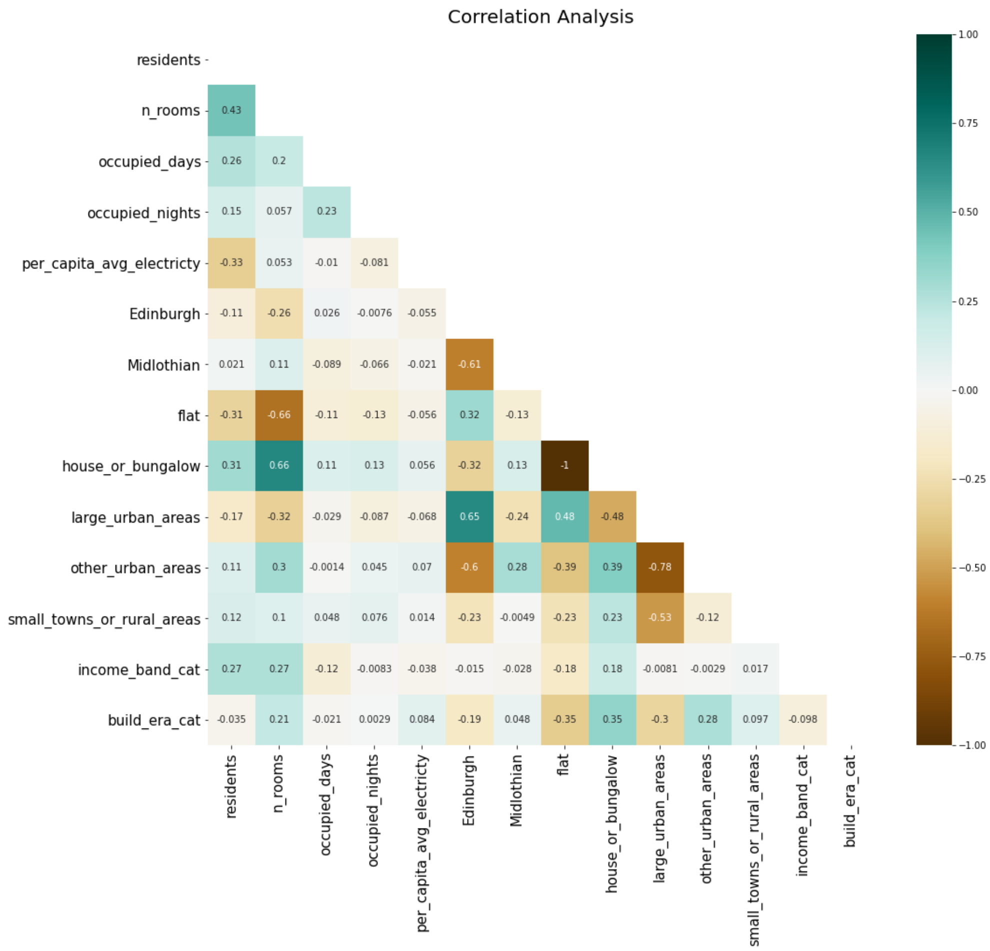

Figure 3.10. Correlation plot of household characteristics

The same can be said of the correlation between electricity consumption and urban areas, which is slightly less obvious, but it might be explained by the fact that people in urban areas have higher probability to live in flats, which therefore tend to consume less energy. There is also an interesting correlation between income band and consumption, which shows that households with higher incomes consume more electricity, probably because of their more expensive lifestyles (they tend to have, at least in this dataset, bigger houses with more rooms and more residents in them, probably children). Unexpectedly, building era seems to have very low correlation with energy consumption.

Similar results have been obtained by applying a Random Forest Regression to the data. Random Forest is a Machine Learning (ML) technique based on Regression Trees. A Regression Tree is a ML method for regression of a continuous target variable from a multi-feature dataset. This method is based on recursively splitting the training dataset, based on the feature that ensures maximum separation according to an *Impurity Function*, which is typically square or absolute error in regression models. Recursive split of the dataset allows to build a tree structure with samples that are similar to each other in each leaf; the obtained tree is used to calculate the value of the prediction for new samples, typically by averaging the label values in the final leaf. The Random Forest method is based on calculating multiple parallel Regression Trees by Bootstraping, which means randomly removing a subset of the dataset for each tree. New sample predictions are then evaluated by averaging the results of each tree in the Random Forest. This method is useful because it decreases the possibility of overfitting, especially with relatively small datasets as in this case. An interesting property of this methods is that the tree structure allows to obtain feature importances, numerical coefficients which give information about how significant each feature is for the regression of the label, in this case the average per-capita daily electricity consumption. Random Forest was applied to the data with 100 Regression Trees, resulting in a model with validation score (coefficient of determination) of $R^2 = 0.43$. The resulting feature importances are shown in Figure 3.11.

Differently from correlation coefficients, which are calculated pair by pair, Random Forest feature importances provide coefficients that are calculated taking into account the whole dataset and the combined effect of different features on per-capita consumption. The importance plot confirms the results of the correlation matrix, with features such as number of rooms and income band being the most relevant for prediction of per-capita amount of energy consumption. Despite having low correlation, building era has high importance using Random Forest. The limitations of these results are however significant; despite the fact that the amount of data is greater than in most similar studies, 255 households is not a very significant number for such kind of statistical analysis, and this also explains the rather low score obtained by the Random Forest method.

This quantitative analysis found relevant correlations between household characteristics, confirming what emerged from the literature on both quantitative and qualitative research [92, 74] on smaller, less nuanced datasets. It should be stressed that, as outlined in Section 2.1, home characteristics are much more difficult to change for user with respect to specific behaviours. Nevertheless, homes with similar characteristics might lead users to similar

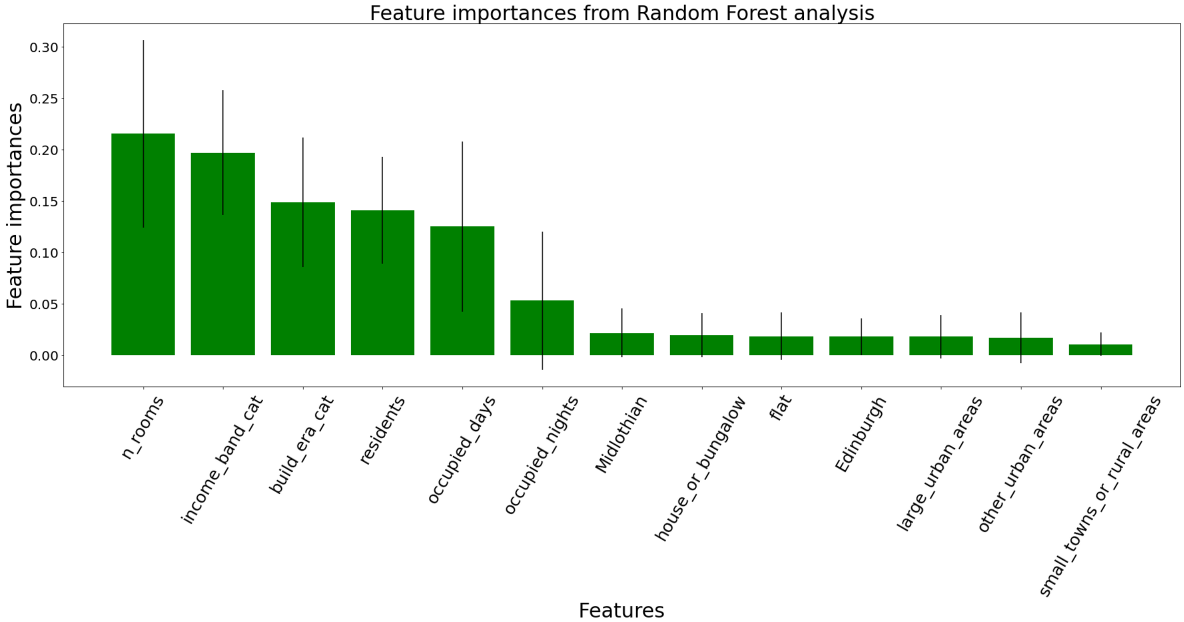

Figure 3.11. Feature importances for per-capita energy consumption from Random Forest model

energy-related behaviors because of similarity of socio-economic factors. The partial results obtained in this analysis highlight the difficulty of obtaining relevant information from computational methods only, besides for very specific tasks, and beg the question of whether a computational approach is the most suited one for behaviour-related inference. Future work in this area might involve combining computational analysis with qualitative data in the form of surveys and workshops, to analyse householders' attitudes and habits in relation to the measured consumption levels.

Chapter 4

System design

This section describes the realization of the prototype of a sonic interaction object that has been developed for this thesis. The object is an Energy-Aware Sonic Carpet. The carpet produces sounds when stepping on it, which are a sonification of different information about the energy consumption of the household. The reasons for choosing this object are explained in Section 4.1, while Section 4.2 describes the realization of the prototype and Section 4.3 explores the sound design techniques and algorithms that have been employed.

4.1 Motivations and needs

Building a physical sonic interface for feedback on electricity consumption requires to define multiple aspects:

- **Physical interface:** the shape, texture, dimension, material and culturally accepted functions of the sounding object, which determines the affordances;

- **Sonification variable:** the data parameters that are going to be represented as sound. Concerning energy consumption in particular, different possibilities are available, related to energy and data trends that have been explored in the literature;

- **Sound design:** the actual sound that represents the status of the sonification variable. The sound output is related to the user's interaction with the physical interface and the state of the sonification variable at any one moment in time;

These three elements are of course interconnected and each one cannot be defined without considering its relationship to the others from a design standpoint. In light of the considerations from the literature review and the data analysis, the idea was to develop a simple feedback object that could seamlessly integrate in the home environment and would be an alternative display of some of the information normally provided by the Smart Meter. Instead of introducing a new object in the house, it is interesting to explore the idea of *augmenting* normal household objects such as carpets, by adding a sonic feedback to the usual interaction with the object.

The energy-aware carpet is thought of as a flexible, non-intrusive object that can be easily embedded in the habits of users. The carpet can be easily "checked" when users prefer, and it is silent for the remaining time, encouraging *sporadic interactions* [37]. Another assumption behind the design is that, becoming the carpet part of the user's habits and routines, it would require lower attentional demand and implicitly communicate information. Several motivations guided the decision of using a carpet as an interface: rugs are flexible objects that can have multiple uses and possible shapes, and they can be positioned in different places in the house. The affordances of a carpet can be connected to routines - like usage of a doormat or a bathroom rug - or more complex, for example in the case of a living room or bedroom carpet. A carpet has a visual and a tactile component, which can be integrated in the feedback structure when designing sonic interactions. Moreover, a carpet provides interesting possibilities for playful behaviour, it integrates within the home environment and it provides a rich palette of possible motion interactions. Most importantly, a priority with this project is to find a way to introduce sounds that are not annoying for users; the carpet allows the user to hear the sonic feedback only when stepping on it, offering a convenient way to avoid constant sounds that could be not well received. Even if there is no pre-defined usage scenario for this particular prototype, one could imagine a user going in and out of the house and receiving a sonic feedback about the state of energy consumption when stepping on their doormat.

Multiple options for sonification variables are available and, despite the fact that only three have been explored in this thesis, they are nevertheless interesting and connected to different usage scenarios. Drawing a parallel with data usually employed in visual feedback, many options have been experimented in the literature. The current prototype focuses on sonification of basic parameters that are usually provided by a Smart Meter. For this reason, the variables that have been chosen for the final prototype are **Real-time consumption**, **Real-time emissions** and **Grid split**, which is the amount of energy coming from different source of electricity at any given moment. These variables have been used to develop two different sonification modes for the carpet, one representing consumption and emissions together, and another one representing energy sources. A positive side of sonifying real-time energy data is that it does not change too fast, unless appliances are turn on or off, so users have the possibility to explore the interface and concentrate on the sounds as much as they want, and the sonic output would not be so different. This aspect could probably facilitate learning to interpret sonic output, and it would be further discussed in relation to the results of the experiment in Section 5.

Once the sonification variables have been chosen, some consideration should be made on how to set thresholds and ranges for the sonic representation of these variables. For example, one might wonder what is the level of consumption after which the sound becomes annoying, or more in general how to set the limits to this kind of feedback system. A similar problem in visual representation is the determination of the range of values and the scale of the axes in a chart, which have to be large enough to include all of the data, but not too large otherwise it would be impossible to calculate the difference between the data points. In the case of the auditory domain, representation is purely time-dependent, and therefore choosing an appropriate range for the variables is even more important because the data is displayed sample by sample, not all at once as in the visual domain . The data analysis in Section 3 is essential for this reason; these thresholds should be set taking into account historical consumption of the household where the carpet is located, otherwise the mapping of data to sounds risks of being useless or exaggerated. Moreover, the thresholds should ideally be set in a dynamic way which would adapt to the ever-changing energy habits of users. The question of how to design such a threshold setting system is out of the scope of this thesis, but it could involve interesting techniques like on-line machine learning systems and user modeling with multiple data inputs.

4.2 Physical and digital prototyping

The development of the physical prototype was an iterative process, involving personal judgement and working with the available materials. The starting point was a basic doormat, a relatively simple object with a clear defined use. To obtain data about people stepping on the carpet, there are multiple available possibilities for sensors [80]. Some examples that have been tested for this project are Force-Sensitive Resistors, handmade pressure sensors with velostat and conductive thread [108, 72], and piezoelectric sensors. The final model of the carpet involves six Force Sensitive Resistors, which have been positioned at equal distance on a wooden surface, as in Figure 4.1, allowing to experiment with different materials on the sensors to test physical response.

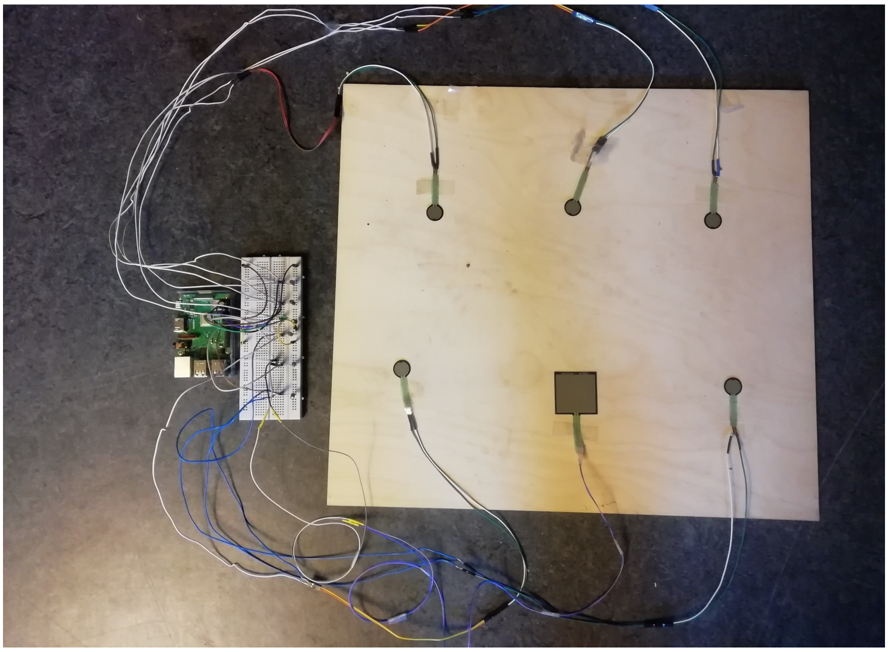

Figure 4.1. Prototyping platform with Force Sensitive Resistors

The chosen carpet for this first prototype, shown in Figure 4.2, is a doormat made of a rough fiber. The doormat has been spray-painted with icons corresponding to different energy sources, indicating the position of the six pressure sensors. The sensors are connected to a Raspberry Pi 4B+ microcontroller. This platform has been chosen with respect to similar alternatives such as Arduino, Bela and Teensy, because it allows to run standalone Python and Pure Data code on it, which could be useful in the case of a future longitudinal study in users' household, in which having a computer connected to the platform all the time (as required by some of these other microcontrollers) would not be feasible.

The resulting carpet prototype that is presented here has relatively low explicit affordances, as sounds can be obtained only by pressing on the icons, which correspond to the sensor positions. This aspect is a known limitation of this prototype, because the usage of a carpet is usually more complex than

Figure 4.2. Physical carpet interface

just pressing on it. It is particularly evident in this case that the sonification is at the same time produced by user input and by energy-related data. Even though in this case user input is minimal - just related to pressure sensor information - it is important to stress that the acoustic perception of the stimuli related to data changes depending on how the users interact with the object. Moreover, being it a first prototype, it is important to have very defined interaction modes and sonic output to obtain a clear evaluation of each of the aspects separately during the testing phase.

The software for the prototype is coded in the programming languages Python and Pure Data. Python has been used to access the sensor data from the Raspberry Pi digital input pins, and to perform a simulation of real-time energy consumption; Pure Data has instead only been used for sound design. The prototyping code has been thought of with flexibility in mind, employing a modular, micro-services based approach. Python scripts communicate with each other using the REST protocol, while communication between Python and Pure Data employs the Open Sound Control (OSC) protocol, a popular lightweight protocol for interactive sound and creative coding applications. The real-time consumption simulator is a Python script that uses data from the KTH Live-in Lab dataset to simulate a REST API exposing consumption, emissions and grid split data on the local network. The micro-services approach is useful because, in a real application scenario, it would be easy to just substitute the micro-service dedicated to server emulation with one that exposes real data without changing any of the operations of the other specific micro-services. A Python micro-service for OSC communication requests consumption data from the REST API and from the sensors on the carpet and sends all of it to the Pure Data script in real time through OSC. Using this approach it is easy to experiment with different sonifications by just changing the Pure Data script that receives the data, without affecting any other component. An OSC receiver Pure Data subpatch, shown in Figure 4.3, is in charge of receiving the data from the OSC protocol, parse it and use it as input for the sound parameters.

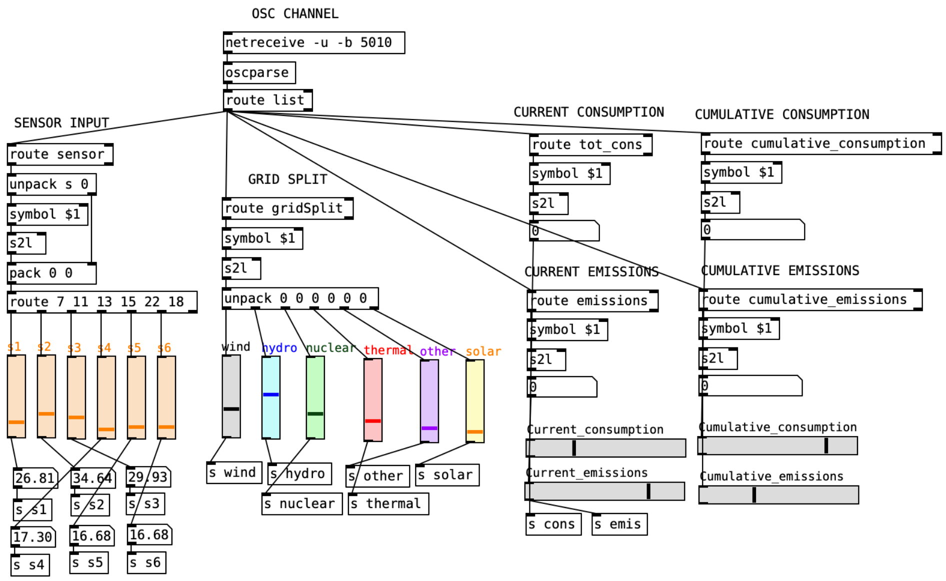

Figure 4.3. Pure Data patch for receiving data through OSC protocol

4.3 Sound design

After multiple experiments with the possible modes of sonification described in Section 2.2.3, the final design involves two different Parameter Mapping Sonifications:

- **Consumption and emissions:** these two quantities are sonified at the same time. The sound corresponding to emissions is played when the user steps on the top row of sensors, while the sonification of emissions is associated to the bottom row of sensors. Consumption data has been sonified by using the Fourier Resynthesis technique, and the sonification of emission data uses consumption data as an input for Frequency Modulation with noise;

- **Grid split:** the sonification of grid split that has been developed could be classified as a parameter mapping and as an auditory icon. It consists of sounds of bells that have been built using additive synthesis, with bells of different pitch being associated to different energy sources;

The main interface of the Pure Data patch is shown in Figure 4.4.

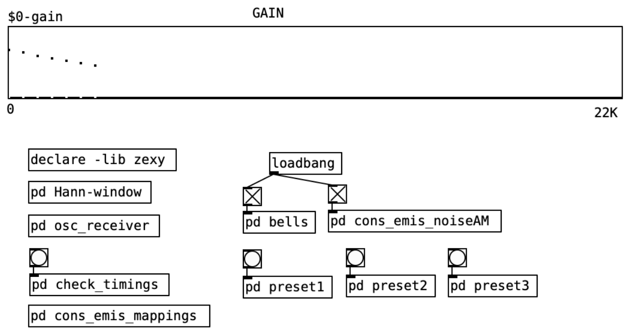

Figure 4.4. Main Pure Data patch for the whole interactive sonification

The sonification of consumption data uses the Fourier Resynthesis technique to produce sounds, inspired by Example I03.resynthesis.pd in the Pure Data example material. This technique is based on producing sounds from a spectral shape that is plotted by the sound designer in a graphical window, using the Inverse Fourier Transform. The resulting sound is obtained by subtractive synthesis, in which white noise is filtered according to the gain levels in the graphical spectrum window, as the one called *$0-gain* in Figure 4.4. The amount of real-time energy consumption in kWh is in this case mapped to the amount of frequency bands whose gain is not zero in the spectrum, after being properly scaled. The higher the consumption the more the higher-pitched frequency bands are activated. As shown in the subpatch in Figure 4.5, some parameters are left to the taste of the sound designer, and are not affected by the data, like the maximum number of frequency bands, the distance between the bands and the gain reduction at each band.

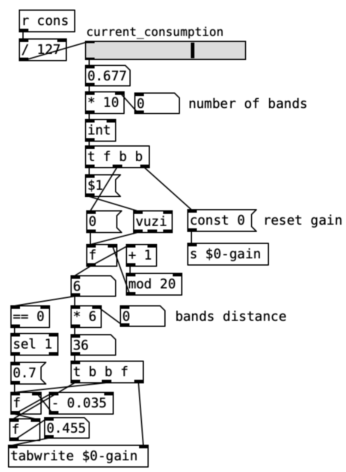

Figure 4.5. Pure Data patch for mapping between electricity consumption and frequency bands

The value of real-time emissions has been sonified by using Frequency modulation with noise. The process is shown in Figure 4.6. The sound from the Fourier Resynthesis of the first sonification is frequency-modulated by low-pass filtered white noise. The amount of emission data influences the amplitude of the modulation noise, the cut-off frequency of the low-pass filter and the amount of noise-modulated signal that is mixed with the original one.

The sonification of Grid Split has been realized using a "bell" sound with a different pitch for each of the energy sources, as implemented in Example D07.additive.pd in the Pure Data example material. These sounds have been built using Jean Claude Risset's (1938 - 2016) study of the frequency components of the sound of a bell. Additive synthesis is based on building sounds with complex spectra by summing up single-frequency sinusoidal components with different frequency ratios. In this case, since bells are not continuous sounds and have an important component related to attack and decay, Risset's implementation involves different attack and decay values for each of the frequency components. In this sonification, the percentage of energy coming from each source has been mapped to the duration in time of the bell sound.

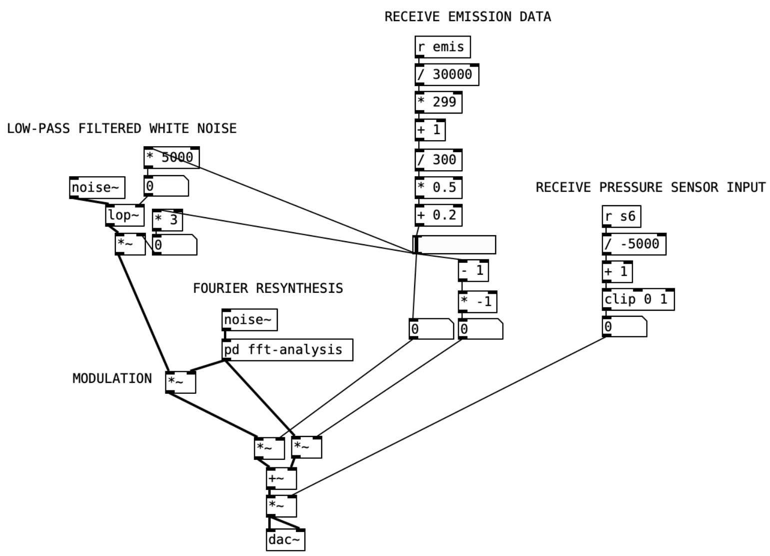

Figure 4.6. Pure Data patch for frequency-noise modulation

Chapter 5

System evaluation

This Chapter presents the evaluation procedure that has been carried out for the prototype. The described content has to be considered as a first testing iteration, part of a longer process of design, and the results of the conducted tests will possibly be used to modify and improve the design of such an object in a second iteration. Section 5.1 describes the theoretical background behind the design of the experiment, while Section 5.2 reports the main results.

5.1 Experiment design

The theoretical background on the evaluation of sound objects and auditory displays is mainly found in two book chapters by Terri L. Bonebright, John H. Flowers [52] and Bruno L. Giordano, Patrick Susini, Roberto Bresin [32]. The study that has been developed to evaluate the Energy-Aware Sonic Carpet has two main goals:

- **Intelligibility of sounds:** determining if the users able to correctly identify the information corresponding to each of the sounds. This aspect has been tested using an *Identification* task [52];

- **User experience:** understanding which aspects of the interface is engaging and interesting to interact with, and which ones could be changed and how. This aspect has been addressed with a survey;

Identification tasks "provide a measure of accuracy for determining whether participants can recognize and label sound stimuli" [52]. They are the simplest way to determine whether participants can associate sounds and information. In order to evaluate the intelligibility of sounds and user experience separately, the identification task has been performed twice, the first time by just listening and the second time by interacting with the carpet interface. This double task allows to evaluate how the interaction with the sound object influences perception and intelligibility of sounds. On one side, the possibility to repeat and compare multiple sounds on the carpet could improve the accuracy, on the other hand the interface could be distracting from focusing on the actual sounds.

To ensure comparability of results, sound stimuli for the Identification task have been sampled at three levels from their continuous mappings. The levels are described in the survey as *low*, *medium* and *high*, and correspond to the respective levels of consumption, emissions or amount of energy from a particular source. As remarked Bonebright and Flowers (2011) [52] and Giordano et al. (2013) [32], it is important to take into account that perception and interpretation of a sound are strongly influenced by the sounds that have been perceived before. To minimize the effect of this in the test results, the selected example sound stimuli have been randomly extracted from all of the possible combinations, and presented to participants in random order. Moreover, before each of the listening tasks, participants listen to the sounds corresponding to the three levels to be familiar with them before starting the Identification task.

The test procedure is organized in this way:

1. **Subject background information:** after signing a consent form, participants write their age, gender and musical background;

2. **Listening test I - Consumption and emissions:** after listening to sound examples corresponding to *low*, *medium* and *high* consumption and emissions separately, participants are asked to identify the correct amount of consumption and emissions in six different sound stimuli. After the listening test participants are asked to rate the sound on five different perceptual scales and freely comment about them;

3. **Listening test II - Grid split:** after listening to sound examples of the bell sounds corresponding to each energy source and to the bell sound duration corresponding to *low*, *medium* and *high*, participants are asked to identify the energy source and the amount of consumption in six different sound stimuli and freely comment about them;

4. **Test with the interface:** participants evaluate the carpet interface in the two alternative configurations (Consumption+Emissions and Grid Split) separately. Differently from the listening tests, sounds are in

this case emitted as the user steps on the carpet. Their task is, in the first configuration, to guess which amount of consumption and emissions the sounds correspond to, and in the second configuration to guess the amount of consumption corresponding to each source among the *low*, *medium* and *high* levels. The experiment is repeated three times with different values;

5. **Open questions:** participants answer to some basic open written questions about their experience with the object and their opinions about it;

5.2 Participants

This preliminary study involved 7 participants (P1 – P7): two female and five males, aged between 27 and 49, with an average age of 37. All of the participants besides P5 stated that they had musical or sound education varying from intermediate to professional level. Tests were carried out in the Media Production Studio within KTH Royal Institute of Technology. It is important to remark that having statistically significant results is not possible with just 7 participants. Nevertheless, in the first phase of design it is not essential to invest resources in a statistically significant user study, because the product is likely to be significantly modified in later stages.

5.3 Results

Results of the Identification task are represented in terms of Accuracy scores. The accuracy of each category of sound stimuli is the percentage of times such stimuli have been correctly identified by participants. The results for the Listening tests I and II are reported in Figure 5.1, the ones for the interface test in Figure 5.2.

From Figure 5.1 it's possible to see that the most effective sonification has been the one of emissions data, in which users were able to identify all the three levels with similar proportions, obtaining an average accuracy of 78.8 %. The same can't be said about the sonifications of consumption and grid split, which produced an average accuracy of, respectively, 54.4 % and 59.9 %. The most confused sounds are the one for *Medium* consumption and grid split. This result could suggest that guessing between the two extremes of a continuous mapping is easier than for the values in the middle, probably

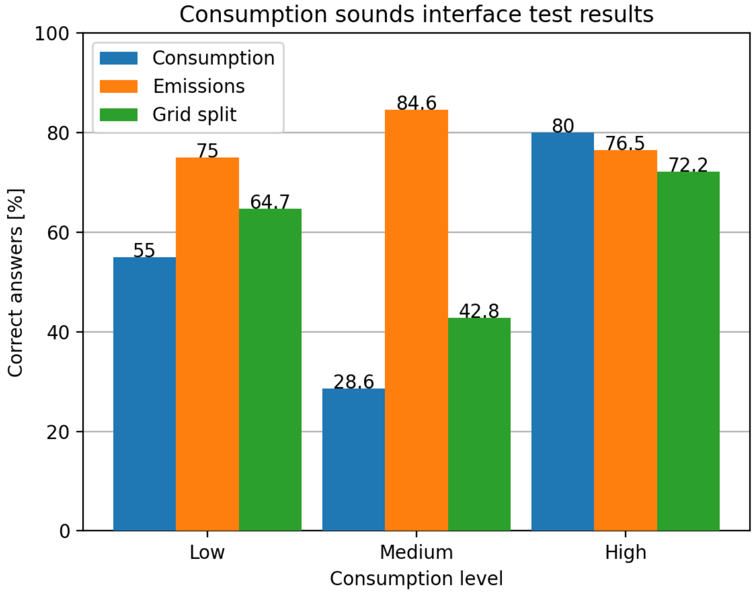

Figure 5.1. Results of the listening tests

because more extreme differences are easier to remember. This challenges the assumption of this sonification that users would be able to identify the status of a continuous variable corresponding to consumption level. Moreover, in a real use case with the carpet interface participants would have time to get used to the sound and they would be able to identify which sounds correspond to which consumption level by checking the actual appliances that are on in the house.

The results of the interface test, in Figure 5.2 are very different from the listening tests. The best performing sonification is in this case the one related to Grid Split, obtaining an average accuracy of 67.7 %, higher than the one obtained in the listening test. This is probably due to the fact that the carpet allows to access the sounds corresponding to the six different sources as many times as the participant wants, and compare them. The higher accuracy can't therefore be attributed to the efficacy of the sonification itself, as much as to the fact that the interface allows to access and compare multiple sounds at the same time. The same is not true for consumption and emission sonification, in which users had poorer accuracy performances with respect to the listening test, respectively of 52.3 % and 61.8 %. The lower accuracy can in this case probably be attributed to the fact that in the listening test users were hearing

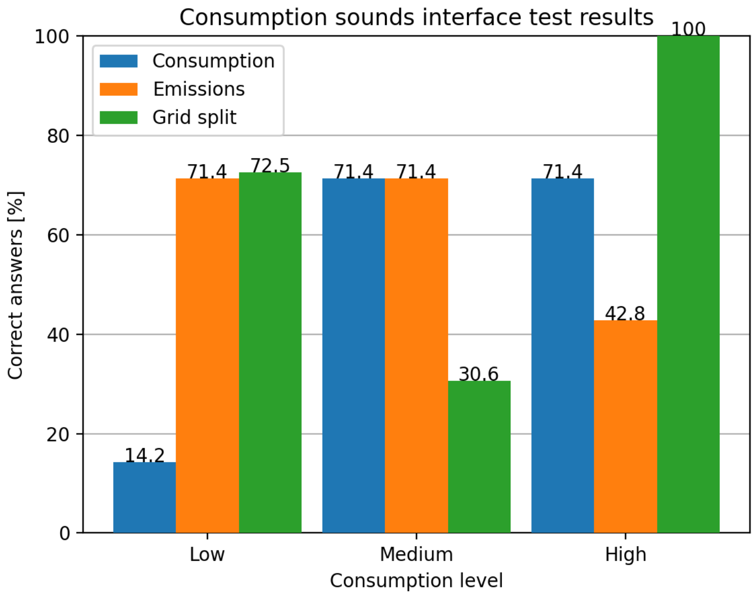

Figure 5.2. Results of the interface tests

different stimuli closer in time, being able to remember the different stimuli and better differentiate among them. The carpet interface presents instead each single sound by itself, providing no reference to contextualize it. This effect is particularly evident in the case of the *Low* consumption sound, which has an accuracy of 14.2 %.

After the listening test, participants have been asked to rate the sounds according to five criteria, which have been selected among the ones proposed in the User Experience Questionnaire (UEQ) Handbook (2019) [95] for design product evaluation, based on relevance to this project. The criteria are expressed as couples of opposite adjectives, and users have to rate the sounds on a scale from one to seven based on how much they feel the sounds are better described with an adjective with respect to its opposite. The selected criteria are *Annoying/Enjoyable*, *Unpleasant/Pleasant*, *Clear/Confusing*, *Understandable/Not understandable* and *Easy to learn/Difficult to learn*. The average responses are shown in Figure 5.3.

The results are on average quite positive, showing that, despite difficulties in identifying the stimuli, participants found the sounds and their purpose to be more clear, understandable and easy to learn than their opposites. This is confirmed by some comments, for example P4 commented “I think with more

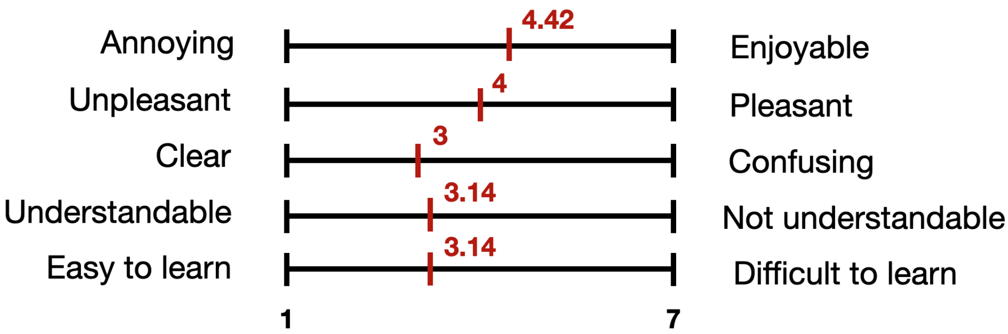

Figure 5.3. Results of the user questionnaire

practice to me these sounds would be very easy to understand" and P7 stated "I think with more of a training period I could get more accurate with my guessing", however P3 commented "It was harder to differentiate between the consumption sounds than between the emissions noise levels". A less positive response was recorded on the participants' enjoyment of sounds themselves, which are not considered particularly pleasant or enjoyable. Despite these averaged results, personal opinions of participants were very different, especially on the first two criteria, with some participants (P2 and P5) finding the sounds more pleasant and enjoyable and some others voting the opposite. Some comments on the sounds include "Could be more of a distinction between high/low consumption. Maybe more of an impact on high frequencies" (P6) and "Sounded like I was in a science fiction movie. A bit tense sounds, maybe stressful" (P2).

Participants were then asked to answer some open questions about their experience with the listening test and the interface:

1. *Can you describe how this experience made you feel?*
2. *What aspect do you like the most and why?*
3. *What aspect do you like the least and why?*
4. *How would you change the aspect that you like the least?*
5. *Can you imagine using an auditory augmented carpet in your home? If yes, what would it look like and what would it sound like?*

Participants' opinions were also in this case very diverse. Despite being very general, the first question is a good example of how people can have different ideas on the presented object and the test experience, some people reporting to be "curious" (P7), "interested" (P6) and others stating that they were feeling "Confused" (P1) or that the experience was "a bit frustrating" (P2). When asked which was their favourite aspect of the experience, some participants referred to the physical interaction with the carpet emitting sounds (P5 and P7), others to the idea of having access to consumption and emission data through sounds (P2, P3, P4 and P6). In particular, P2 stated "I like imagining how this could fit in my house, what appliances it would work with etc. I think this is great that it brings up these thoughts!". When asked about their least favourite aspects, some participants said that it was the uncertainty of some of the feedback, others criticized the sound of the bells, referring to them as "horrible" (P5) and difficult to understand (P3). A particularly interesting feedback came from P2, a designer, which pointed out: "The interaction with feet why? I don't feel like it's a natural mapping". Consequently, most of the answers to question 4 were about modifying the sounds, proposing "bird chirping" (P5), changing "timbre" (P6) and "add more sonic differences" (P7). When asked if they would imagine to have an auditory carpet in their home, five participants out of seven answered positively. Some participants described how they would use it, for example "would be a good check that the lights are off and the stove is off etc." (P3) and "Possibly positioned at an entrance to a room or apartment so I could monitor as people come and go" (P4). P2 commented that they would use it if "it would fit the aesthetics of my home and the actions I normally do at home" (P2), while P7 interestingly observed "I'm not sure it would matter to me that it is connected to data".

Overall, the tests yield very diverse results. Even though most participants are interested in the idea of having a sonic feedback about energy, the chosen sonifications were not very successful, being most times difficult to interpret and not considered very pleasant. The test provided insight into the aspects that participants were mostly interested in - such as gaining information about consumption and having a fun responsive interaction - and the ones they would change. The most interesting result probably concerns the intelligibility of sounds, showing that participants had difficulties in placing sonic parameters on a continuous scale without hearing a sonic reference close in time, in this specific sonification. This aspect could be solved if, as pointed out by some of the participants, the carpet was part of a daily routine and they had time to get used to them. This assumption is however not certain and should be proven by a longitudinal study, after re-designing the prototype based on the results of this test.

Chapter 6

Discussion and future work

One of the objectives of this thesis was to investigate households energy data using quantitative methods of analysis, to gain information about how energy is used, and thinking how this knowledge can be used to inform sonic interaction designs. The literature review phase provided an understanding of the possibilities for data analysis and the status of the field of behaviour change interventions for energy efficiency. The data analysis phase confirmed the findings in the literature review, showing that households are indeed very diverse and have diverse habits which can be very difficult to identify by only using computational methods. This has shown that in future research, a more thorough analysis of per-appliance data could prove useful to obtain meaningful information, particularly when the numerical measurements are complemented with qualitative data. This kind of analysis would likely be more fruitful if focused on a specific behaviour or appliance. The same can be said about the sonic interactions to be designed in future experiments: in this context, the Energy-Aware Sonic Carpet should be considered as an exploratory design, with the aim of investigating affordances and metaphors related to energy, sounds in the household and intelligibility of the basic information provided.

The prototype proved to have some success in terms of user engagement, with many people being interested in the physical interaction with it. Most of the participants were also interested in the information provided by the carpet, and reacted positively to the idea of having such object in their homes. However, the tests also showed that many aspects of the design should be further investigated and modified. It is envisaged that next design will need to involve sounds that are more subtle, and better integrated with the home environment and the affordances offered by the carpet. More consideration should be given to how this object would be used in a real-life setting. The role of the object in the sonification metaphor should also be further considered: despite the carpet being a flexible interface, it only has a loose metaphoric or cultural connection to the concept of energy (carpets in living rooms and bedrooms might be easily connected with the idea of warmth and heating), and this should be taken into account, as it constitutes an important part of the aesthetic and user experience.

Another outcome of the user test is specifically related to the sounds themselves. Users had very diverse opinions on the pleasantness of sounds, and the ability to interpret their meaning was also very different among participants. A deeper investigation of the sonification component is needed. A wider investigation of the sonification space could be carried out independently from the physical interface, and only the successful results could then be tested with the interface. An interesting direction could be developing experiments based on different evaluation procedures among the ones described by Bonebright and Flowers (2011) [52]. For example, an *Attribute ratings* task could be useful to compare different sound designs in terms of user tastes and preferences. A *Discrimination* task could be used to map perceptual distance among a set of sounds, which would be really useful in a future iteration of the experiment that involves more complex sound systems, while a *Dissimilarity ratings* or a *Sorting* task would be used to make sure that the mappings of data to sounds are correctly interpreted by the users. It is also important to further investigate the role of auditory memory in the evaluation phase. In a realistic usage of these sound objects, users would not experience sudden changes in data since the sonification refers to a real-time state variable, and energy usage does not change that fast. The users' ability to interpret the meaning of the data would therefore need to rely on the memory of a repeated repeated experience in everyday life for a period of time. This is an assumption that could not be evaluated empirically on this occasion but, as already suggested in Section 5.2, should be investigated in a longitudinal study.

To investigate suitable sonic interactions, it would be useful to gain an understanding of home soundscapes, and householders' personal relationships to the sounds that are already there. This could be done by a deeper analysis of the literature on the subject on a sociological and psychological point of view, and by running workshop and field studies.

This project has shown the incredible complexity and diversity, with respect to energy consumption and design-based interventions, of household environments, and has started to dive into the design possibilities that this context offers. If computational analysis confirmed that socio-economic background has a determining effect on absolute level of consumption, user tests showed that participants had very different capabilities to interpret sounds, and preferences related to pleasantness of sounds. This calls for a different approach to design interventions, which should be less standardized and provide users with more decision power both about the sonic content and the usage of the introduced sonic objects. Future work on the design side could be either focused on very specific interactions and feedback on specific actions, or on building very flexible and adaptable objects that leave participants freedom to customize them and use them as they feel would integrate in their habits.

Chapter 7

Conclusions

This thesis has investigated sonic interaction design methods to promote energy efficient behaviour. The multidisciplinarity of the project required a review of literature in multiple different subjects, which was especially important to identify a framing of the problem that could provide opportunities for sonic interaction-based interventions. In this context, the data analysis phase was necessary to inform the design process, identifying which aspects of the data could be interesting from a design standpoint and exploring the possibilities the data offers as a design material. Based on knowledge of the data, a basic prototype of sonic interaction design was developed: an interactive sonification of real-time energy consumption, emissions and grid split, accessed from a carpet interface. A user test was developed to gain information about sound intelligibility and user experience, which provided interesting information about possible future directions of this research.

As mentioned in the literature review, very few experiments of real-time sonification of home energy data had been explored in previous research projects, and the overall field of household sonic interfaces is a fairly new research area, so the work of this thesis should be considered as an initial exploration of the possibilities of the field, with the aim of identifying interesting directions and possible pitfalls. The experiments allowed to identify aspects to be further explored in future work and ideas that should instead be excluded. Moreover, analysing the problem from many different angles coming from different disciplines allows to question the premises of energy efficiency and energy-efficient behaviour, and even their definitions, which significantly change if the problem is considered from an engineering, environmental psychology or design point of view. Far from a purely engineering task, designing sound-based feedback systems for the home has meant questioning the role of users, the role of technology and the role of sound in this environment. Despite these reflections, the assumption behind this project is still that specific user behaviour in relation to energy could be affected by feedback. This assumption is far from being verified, and future research should involve questioning the notion of energy efficiency on a broader level, beyond energy feedback, developing designs that challenge the current paradigm of energy usage, improve awareness of the broader implication of energy consumption and empower users to creatively engage in the discussion about energy.

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